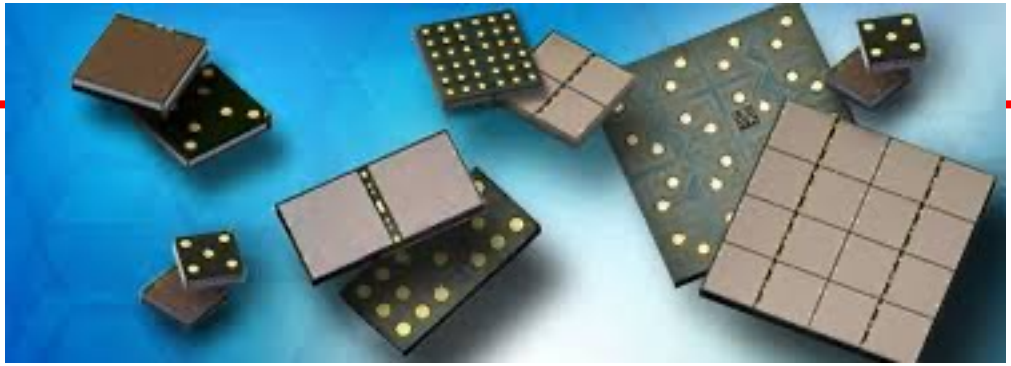

Silicon Photomultipliers: applications in Particle and Nuclear Physics

P. Antonioli
INFN - Bologna

Open Physics Hub

Summer School on Physical Sensing & Processing
Bologna, 17-21 July 2023

Outline (and disclaimer)

INFN
Istituto Nazionale di Fisica Nucleare

- ✓ A little bit of history and a general introduction to SiPM: achieve a dictionary
- ➢ Calorimetry
- ➢ PID
  - Plastic scint/veto
  - RICH
  - Time-of-Flight
- ➢ Potential impact of new technologies

"emphasis on sensors, not on detectors"

DISCLAIMER: This is not a course, but a lecture. Tried to mix a general introduction to the sensor, with highlights from *some* detectors/applications so far + *some* recent R&D progress in the technology

LINK effort: many slides with many links.. You can deepen your knowledge. This talk should not be an end, but a start for your studies if interested to SiPM!

SiPMs turning 25…. (or 30…)

ELSEVIER

Nuclear Physics B (Proc. Suppl.) 61B (1998) 347–352

PROCEEDINGS SUPPLEMENTS

Limited Geiger-mode silicon photodiode with very high gain

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[a]Moscow Engineering and Physics Institute (MEPHI), Russia

[b]Centre of Perspective Technology and Apparatus (CPTA), Moscow, Russia

[c]DESY, Hamburg, Germany

The novel type of the Silicon Photodiode – Limited Geiger-mode Photodiode (LGP) has been produced and studied. The device consists of many $\approx 10^4$ mm^{-2} independent cells $\approx$10 mkm size around n^+ -"pins" located between p-substrate and thin SiC layer. Very high gain more than 10^4 for 0.67 mkm wave length light source and up to $6 \cdot 10^5$ for single electron have been achieved. The LGP photon detection efficiency at the level of one percent has been measured.

1. INTRODUCTION

The high gain (> 10^4) silicon detectors may have important applications in high energy and nuclear physics as:

-compact insensitive to the B-field fast photodetectors for electromagnetic calorimeters and preshower detectors.

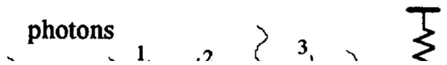
-small size ($\approx$0.1 mm^2) single photon detectors for scintillator fibre trackers.

-very fast ($\leq$100 ps) pixel particle detectors for time of flight measurements.

In this paper the different modifications of such a photodiodes and their mode of the operation have been presented.

2. THE STRUCTURE OF PHOTODIODE

The schematic photodiode structure (basic version) is shown in Fig.1. It consists of pin like



Around 1990 the initial prototypes of SiPM (**MRS** Metal- Resistor Semiconductor APD's) were invented in Russia (*V.Golovin,Z.Sadygov,N.Yusipov (Russian patent#1702831, from10/11/1989)*

Pioneering work in Moscow, MEPHi/CPTA as well as at JINR/Dubna described in:

- Saveliev, NIMA 442 (2000) 223
- Golovin, NIMA 539 (2005)
- Dolgoshein, NIMA 563 (2006)

And references therein

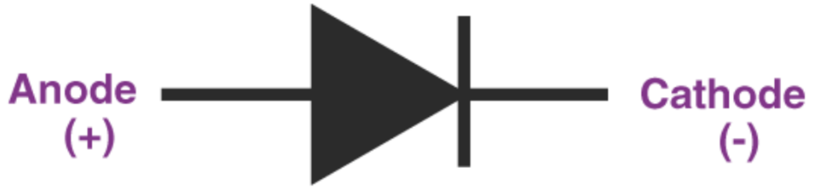
According to this nice talk by E. Popova (MEPHI) at 2019 Rindberg School **SiPMs are turning 30 exactly this year**

What is a SiPM? (in few – historical - steps) (I)

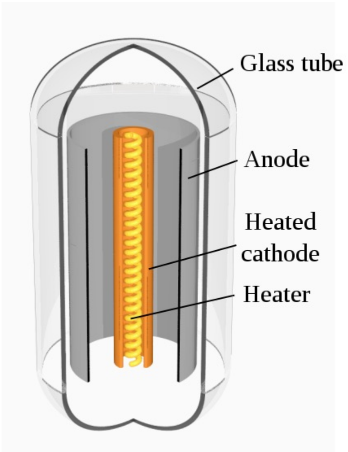
Remember first what is a **diode**:

A diode is a two-terminal electronic component that conducts electricity primarily in one direction. It has high resistance on one end (→∞) and low resistance (→ 0) on the other end.

We speak therefore about asymmetric conductance of the diodes.



First engineered as thermionic valve (or thermionic tube) (Fleming, 1904): it uses electrons emitted from a hot cathode. Electrons can flow in only one direction!



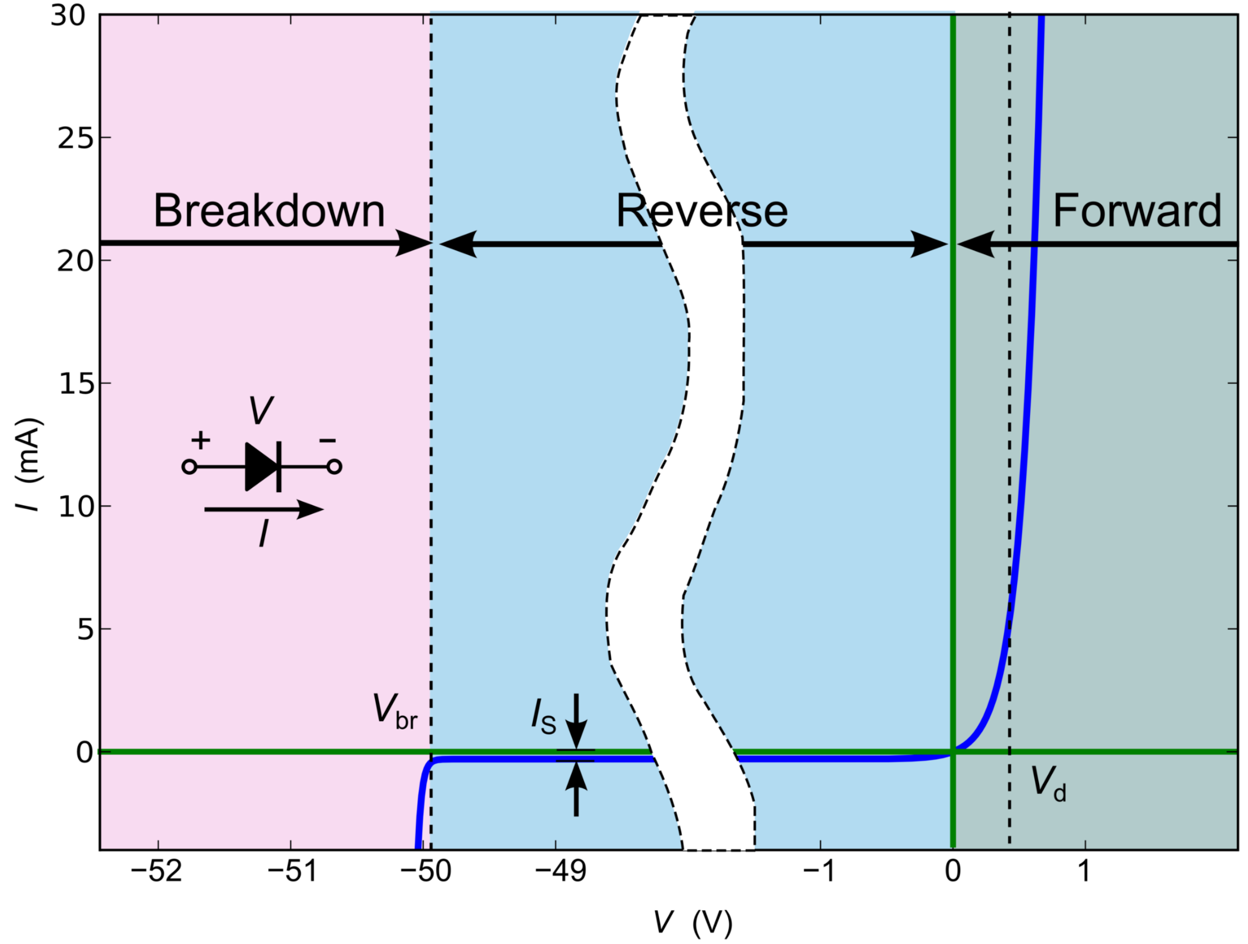
What is a SiPM? (in few – historical- steps) (II)

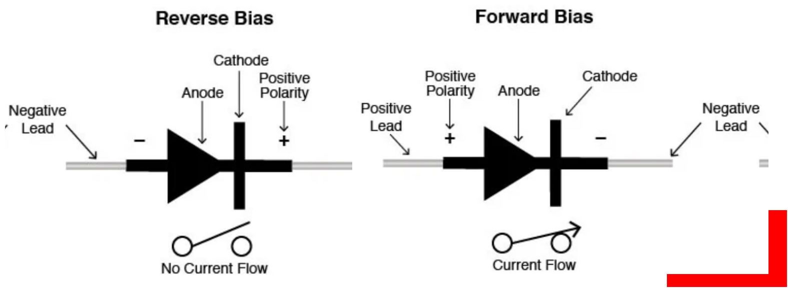
Remember about **semiconductor diode**:

Made by a p-n junction connected to two electrical terminals.
(discovery of asymmetric electric conductance across crystalline mineral and a metal dates back to 1874)

Nowadays semiconductor diodes technology largely based on silicon. Impurites on the silicon are added to create regions with negative charge carriers (electrons) → n-region o positive (holes) → p-region. The depleted region acts as an insulator and its width is regulated by the **built-in potential** (it stops recombination)

- Without voltage applied: momentary flow from n to p-side --> "depletion region"
- With voltage applied (higher to p-side) → electrons can flow through the depletion region (not viceversa) → a diode!





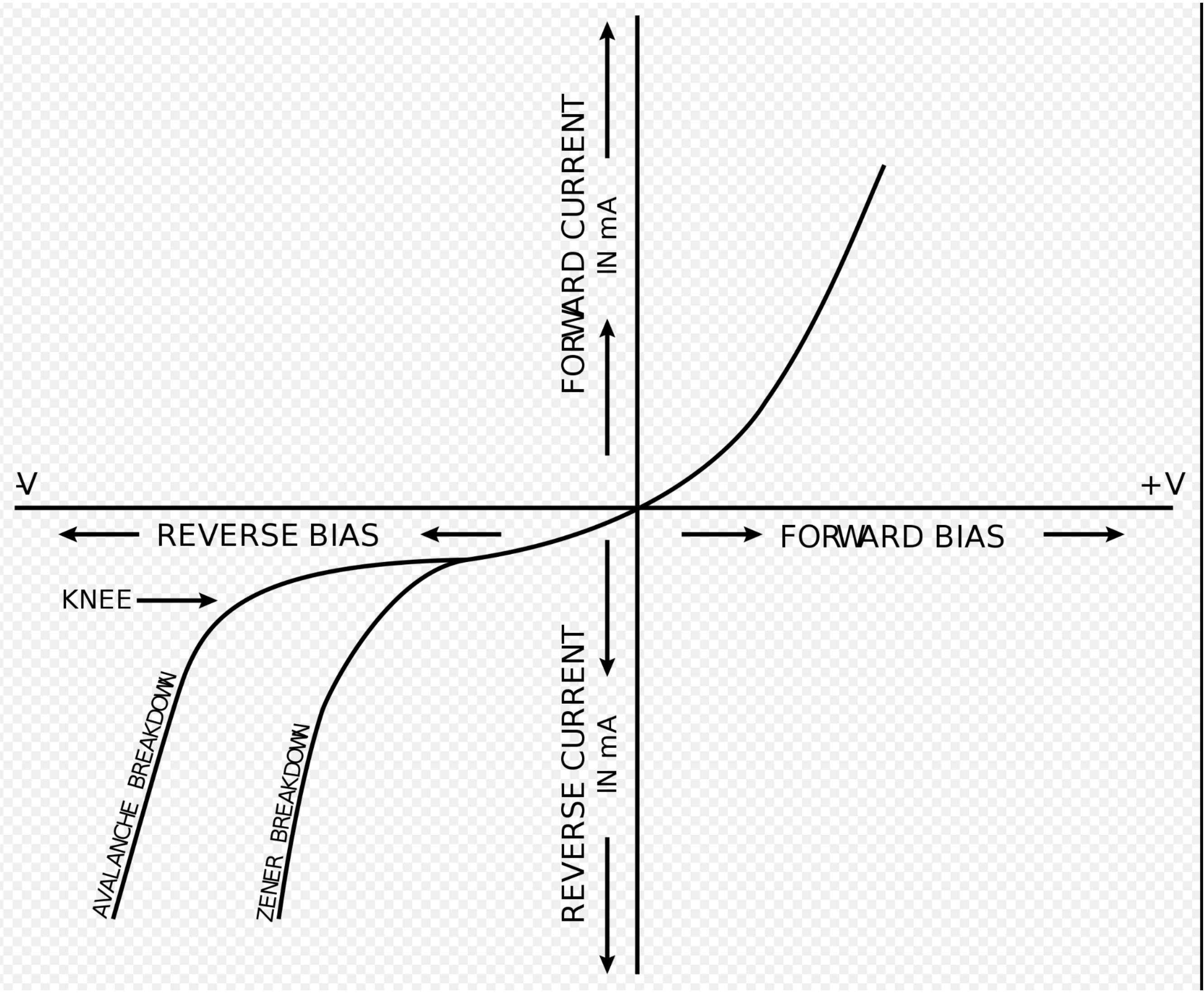
What is a SiPM? (in few – historical- steps) (III)

What is an **avalanche diode?**

At large reverse polarity something different happens!
This happens beyond PIV (Peak Inverse Voltage).

Essentially mobile electrons at sufficiently high V before reaching n-region can free other bound electrons… and this creates in turn a high flow of current (“avalanche”)

The diode is no longer an insulator.
V ”breakdown” concept”

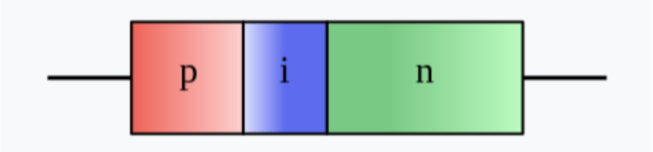


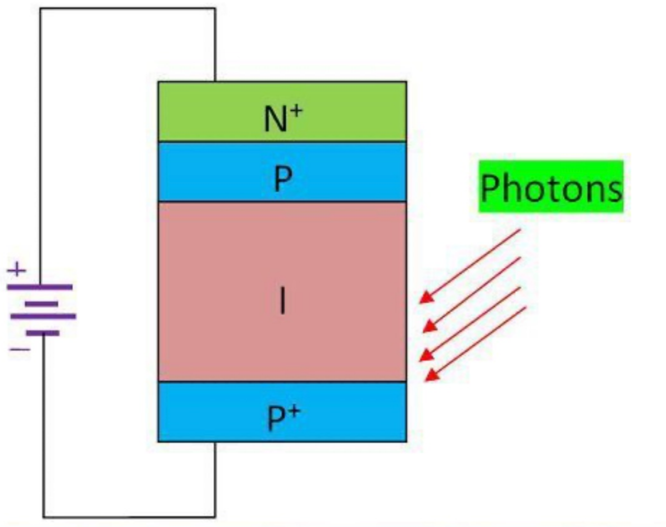
What is a SiPM? (in few – historical - steps) (IV)

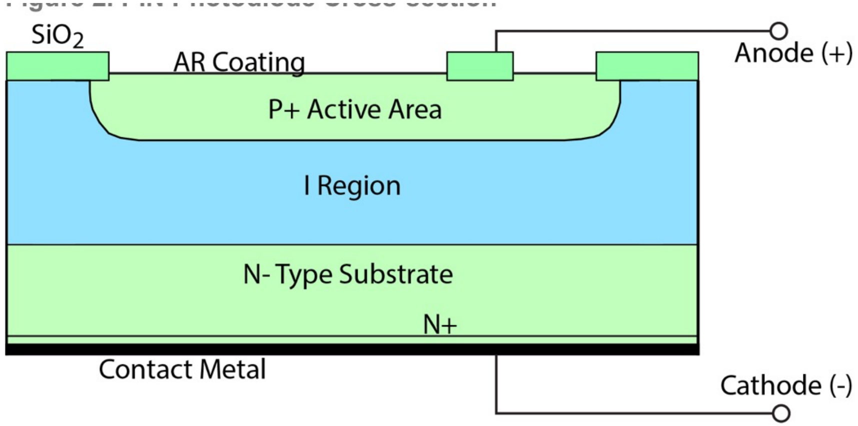
What is instead a **photo diode?**

photodiode is based on a **PIN junction**

- The intrinsic region increases the depleted region with respect to pn junction: larger and constant-size
- This increases the region where an incident photon can generate an electron-hole pair → photodiode
- Note photodiodes are operated in reverse voltage: the voltage sweeps charges out of depleted region → current





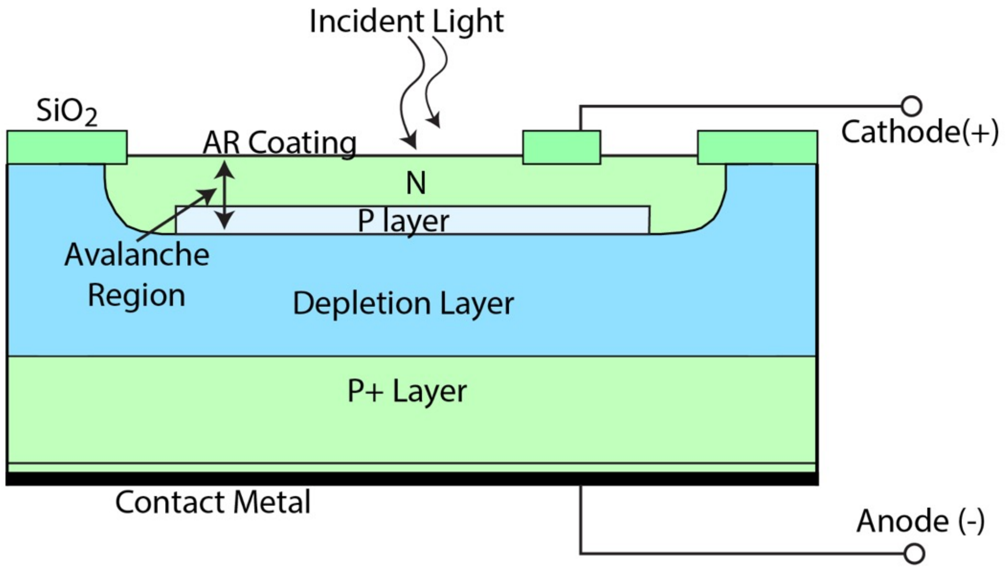


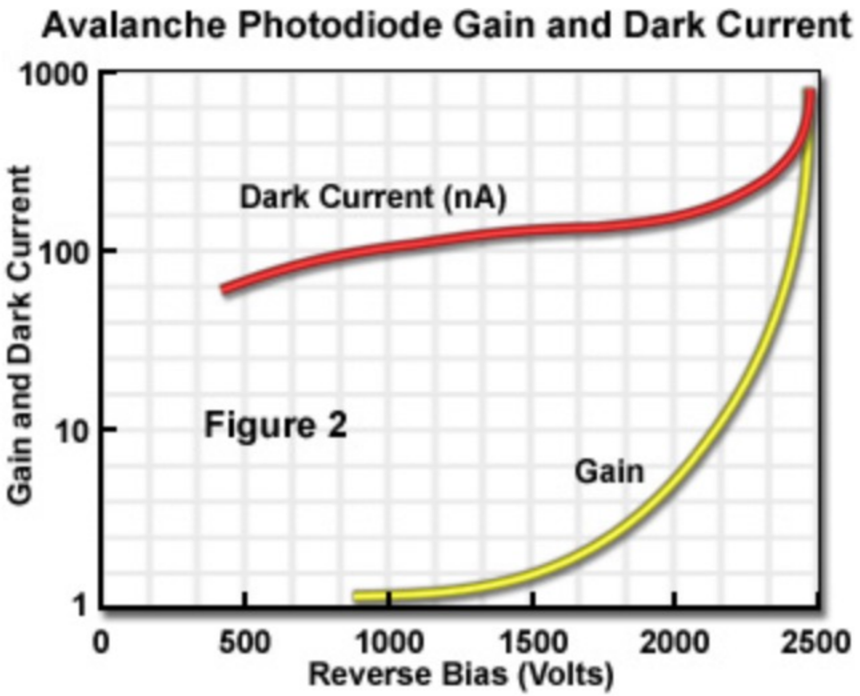
Jun-ichi Nishizawa invented both photodiode and **avalanche photodiode** (1950-1952)

What is a SiPM? (in few – historical - steps) (V)

Let's move to an **avalanche photodiode**

If you apply high reverse bias and the field is high enough carriers (electrons in particular) can generate ("impact ionization") other charges in the depletion region: current will flow! → avalanche

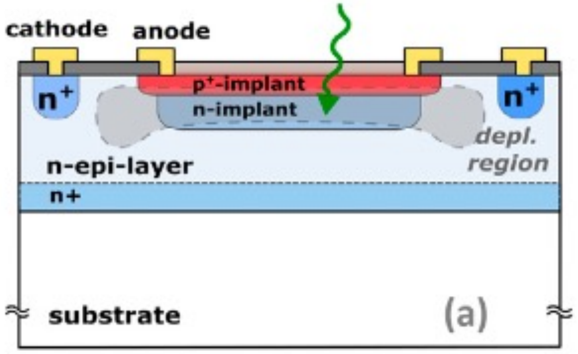




Similar to PIN but depletion region relatively thin
Concept of avalanche similar to what we do in traditional PMT via dynodes

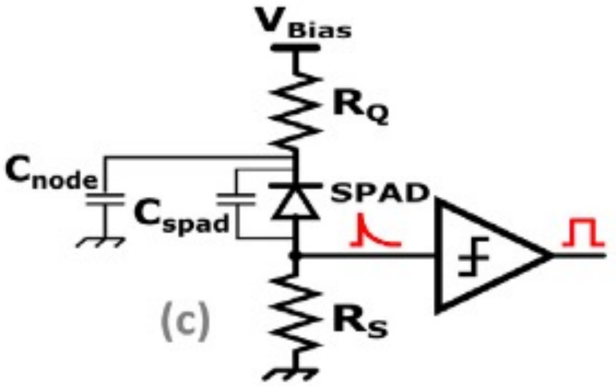
What is a SiPM? (in few – historical- steps) (VI)

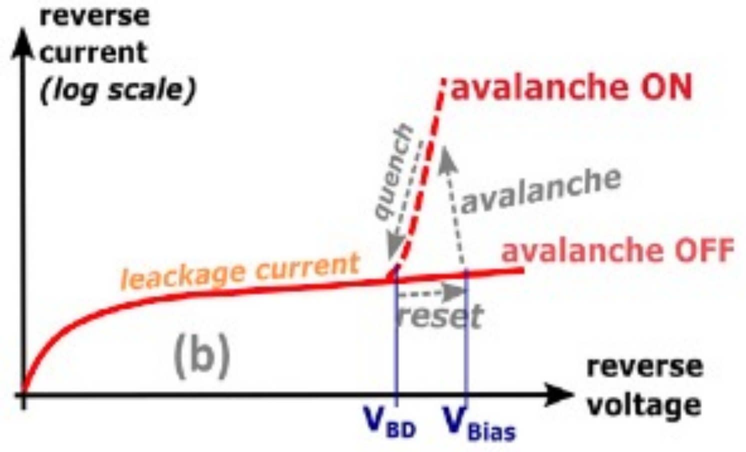
Penultimate step toward SiPM is the **SPAD concept**: **Single-photon avalanche photodiode**



SPAD:

- APD designed working **beyond breakdown voltage**
- **Electrical field can reach few 10^5 V/cm**
- Avalanche multiplication as internal gain mechanism, but a single carrier injected can trigger self-sustained avalanche
  → Geiger-mode (Gm-APD)
- Single photon sensitivity
- Need of a "quenching circuit"



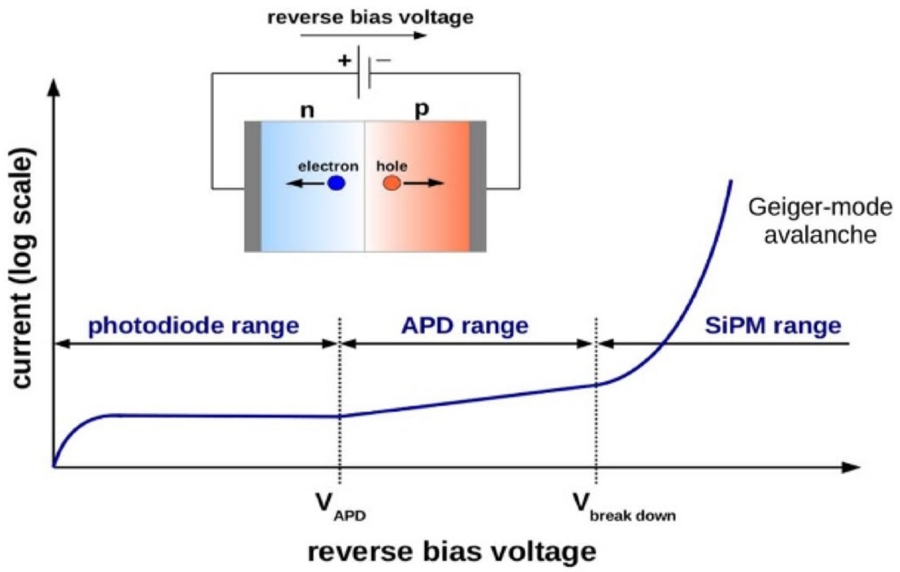


With current increases R_q creates a voltage drop such the V_{bias} goes below breakdown and avalanche stops.

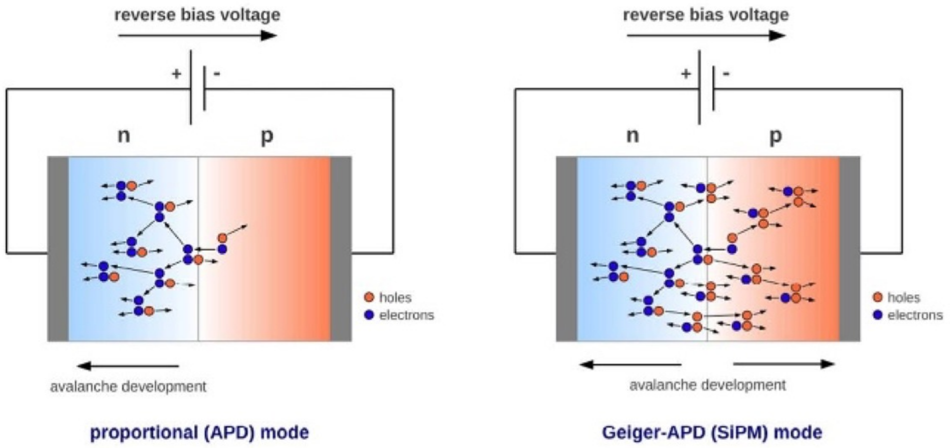
$$\tau_{reset} = R_q \cdot (C_{SPAD} + C_{node})$$

Figures from F. Acerbi and S. Gundacker, NIM A 926 (2019) 16-35

In SPAD avalanche is self-sustained



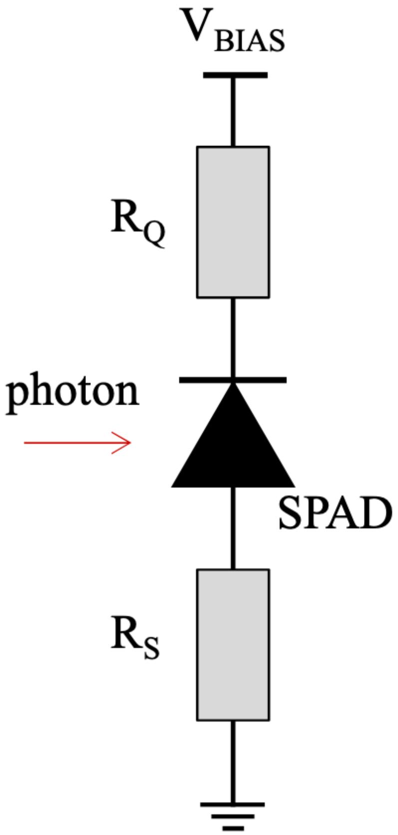
(a)



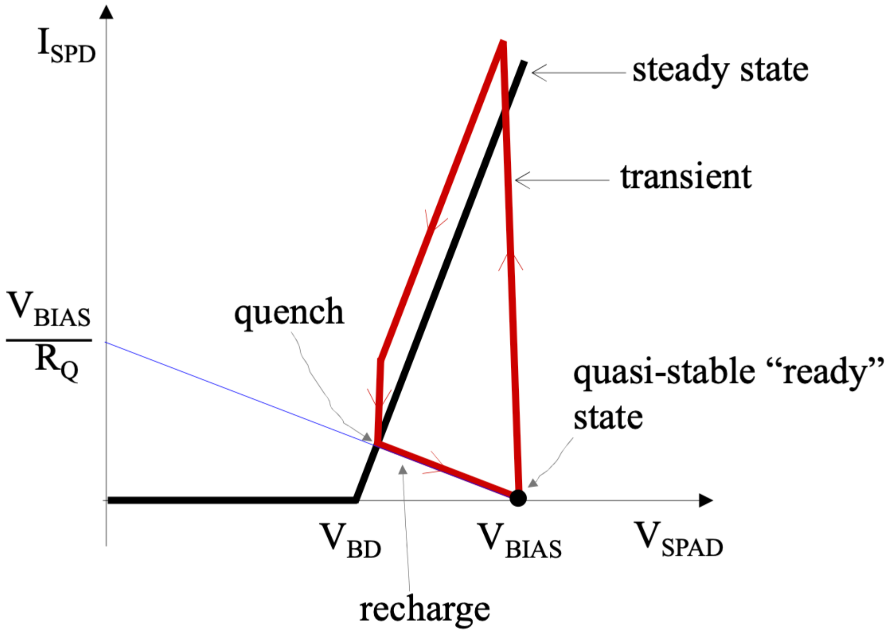
(b)

In the APD only electrons can sustain the avalanche, whereas in a SPAD holes will perform impact ionization as well.

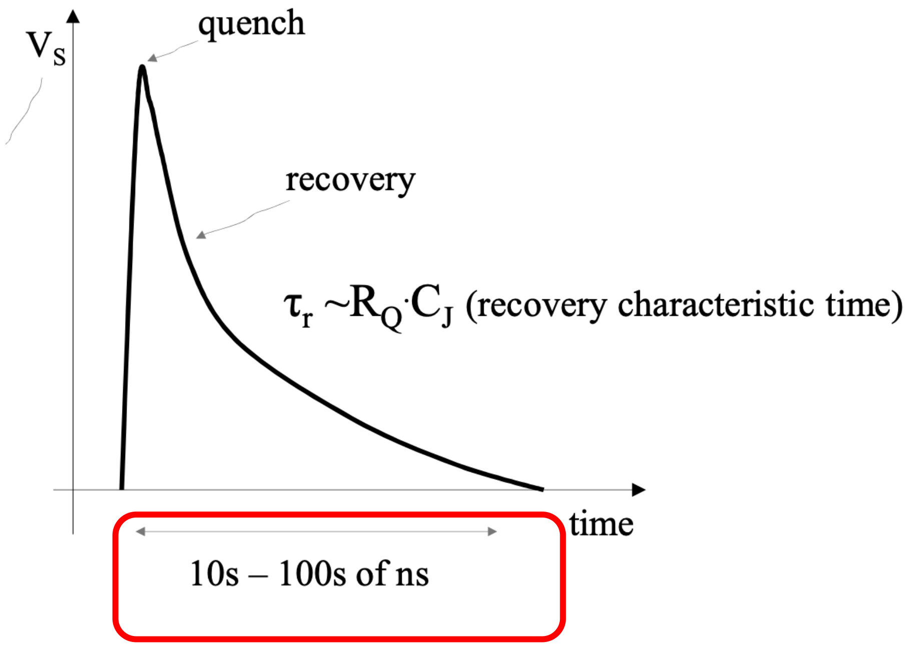
SPAD: further details on quenching and signals



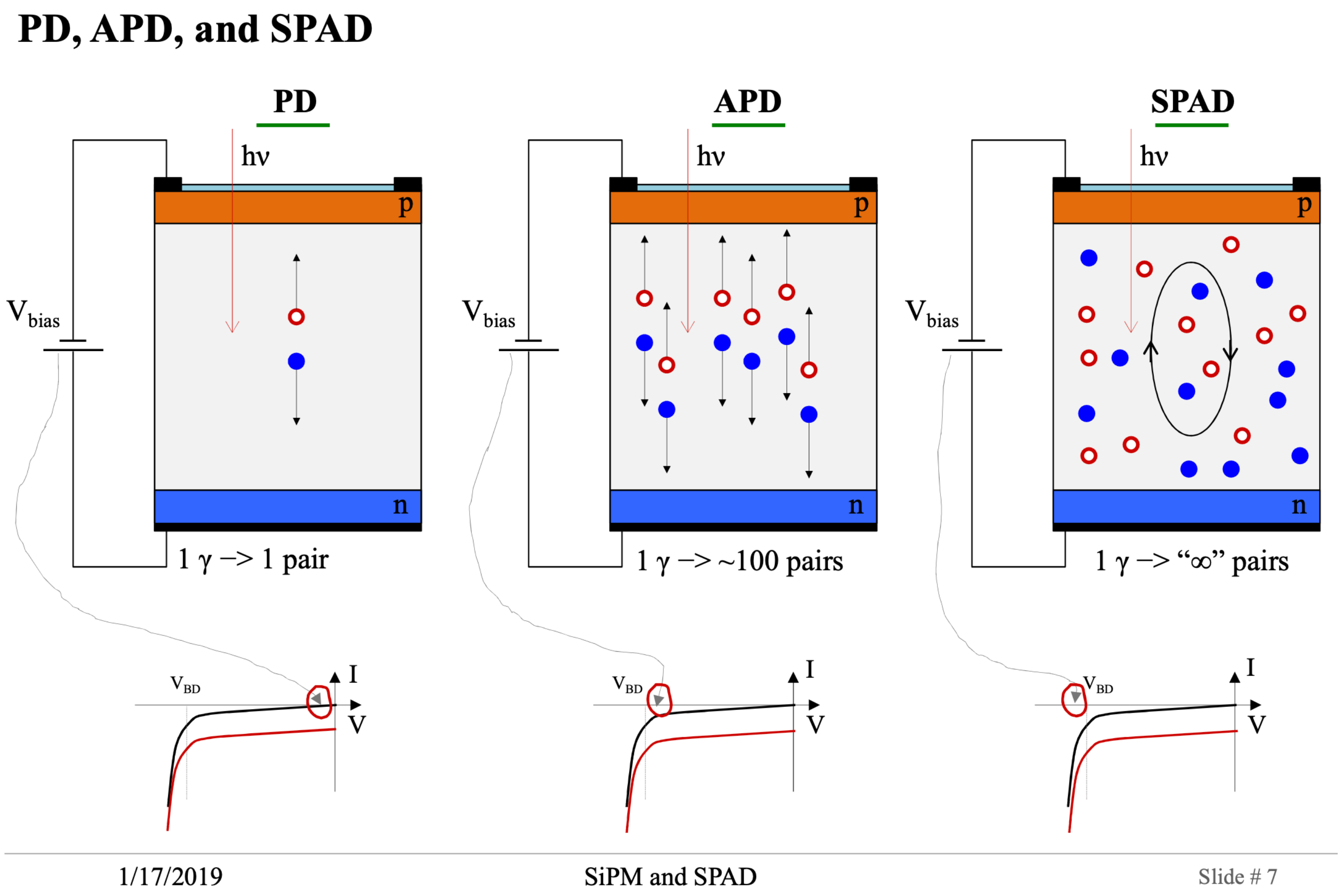
$R_Q >> R_S$



Voltage pulse on R_s due to avalanche



A first summary after 11 slides

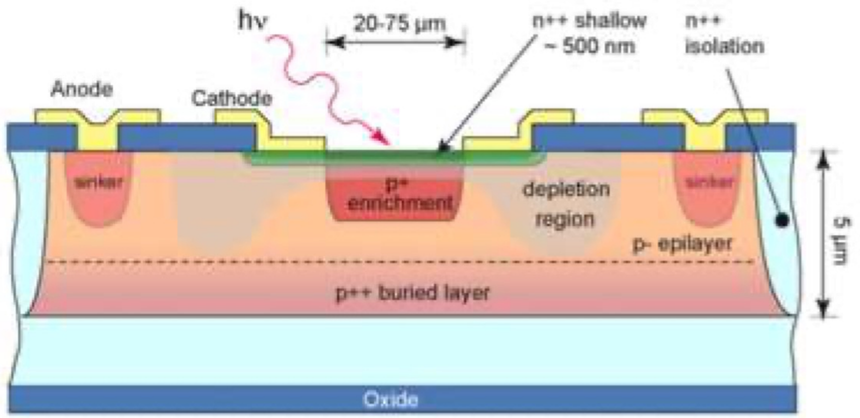


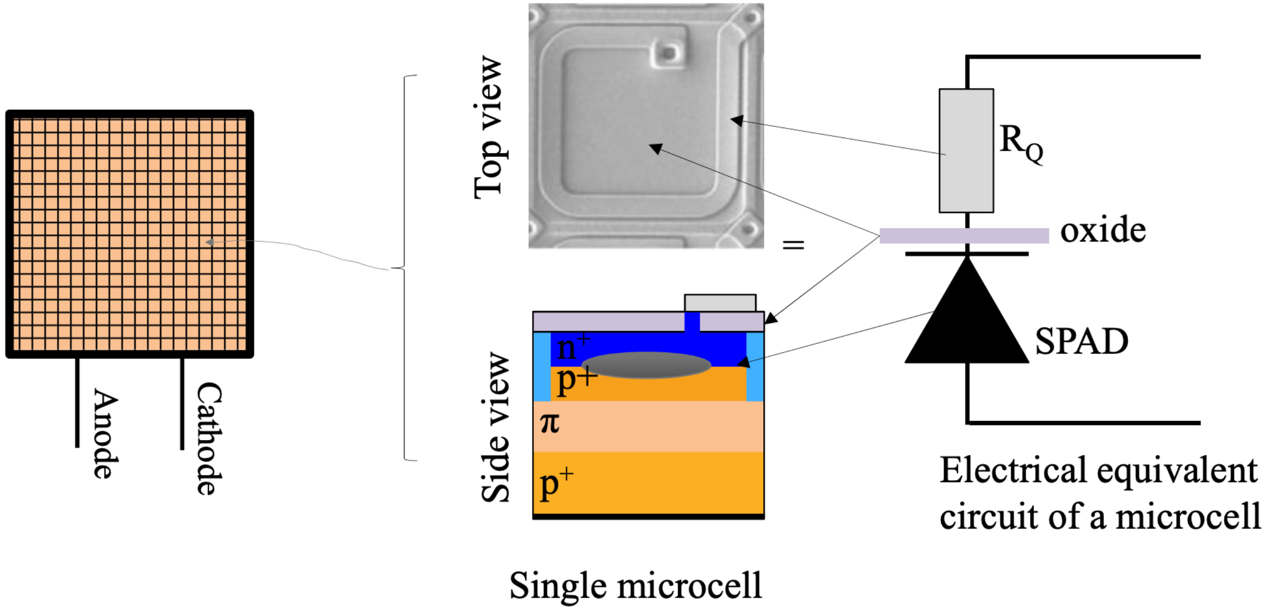
(courtesy: S.S. Piatek, "SiPM and SPAD: Emerging Applications for Single-Photon Detection ")

What is a SiPM? (in few – historical - steps) (VII)

Last step toward SiPM is the **SPAD array concept**:
How can we pack many SPAD in a suitable sensor?

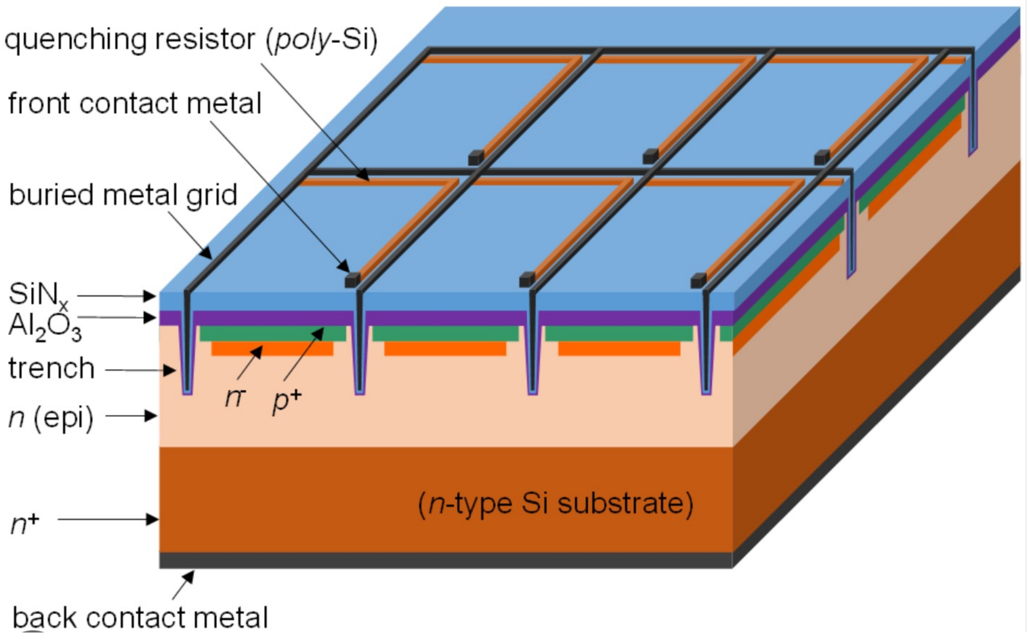
Structure of microcell replicated in an array!

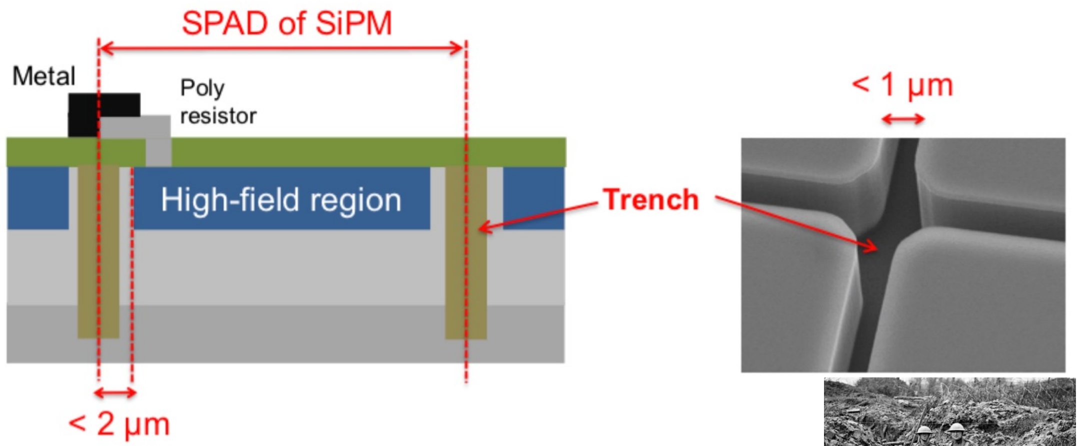


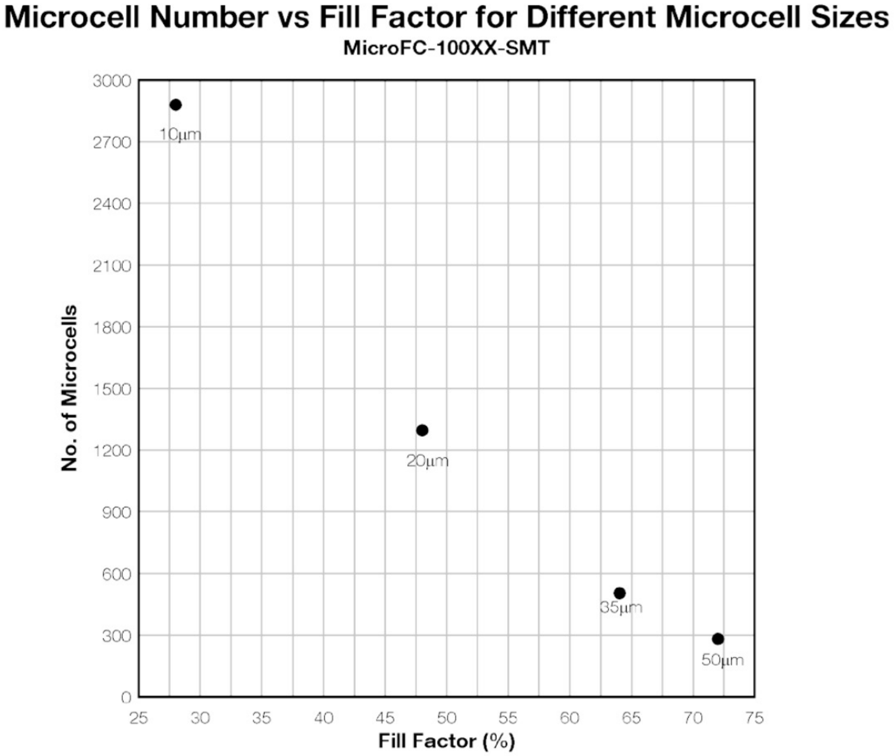


Side note:
SiPM is not an imaging device: all microcells share common current summing all cells!

SiPM: microcells, arrays and trenches





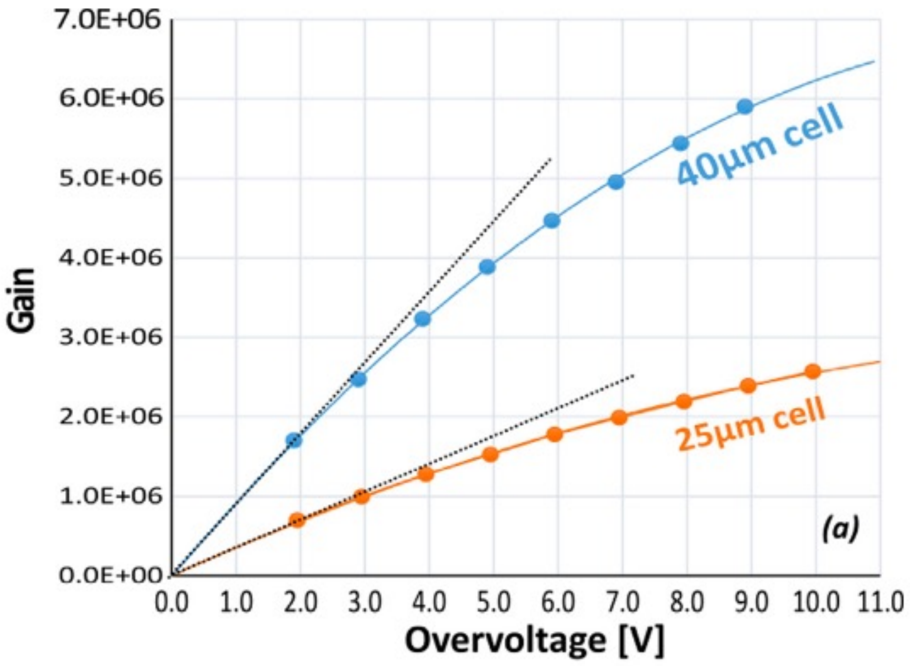


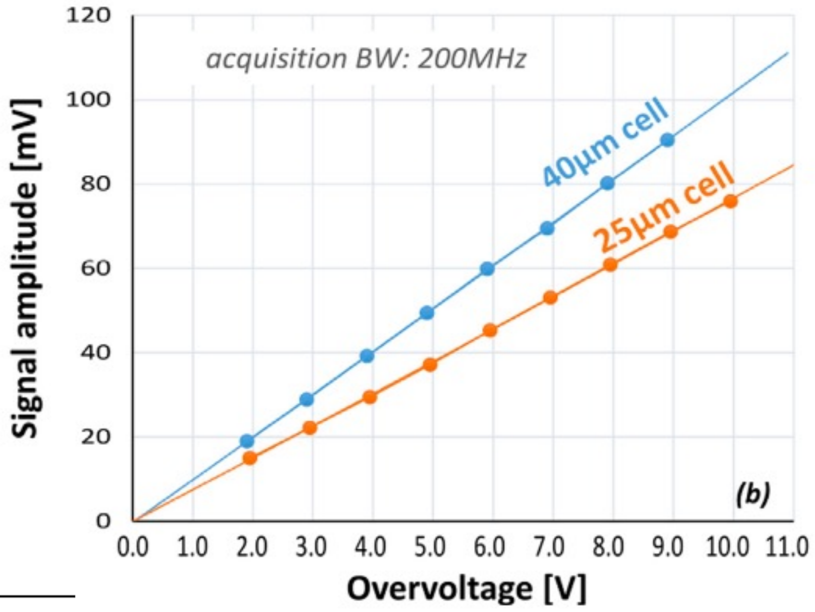
- Typical micro-cells size is between 15-75 um
- Typical SIPM array size is 3x3 mm^2 o 1x1 mm^2
- Using 3x3 mm^2 → typically 200x200-40x40 SPAD

Typical tradeoff between microcell size and **fill factor**

Poly-Si → polycrystalline silicon → high R

SiPM: gain and signal amplitude



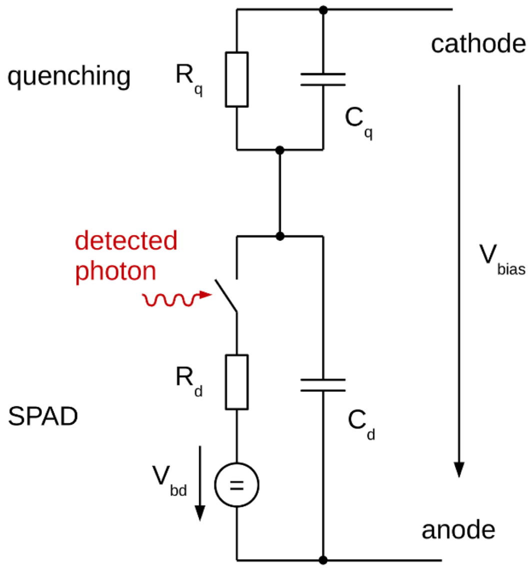


Overvoltage (V_{over} or OV or V_{OV}) = V - $V_{breakdown}$

Gain much higher than in APD!

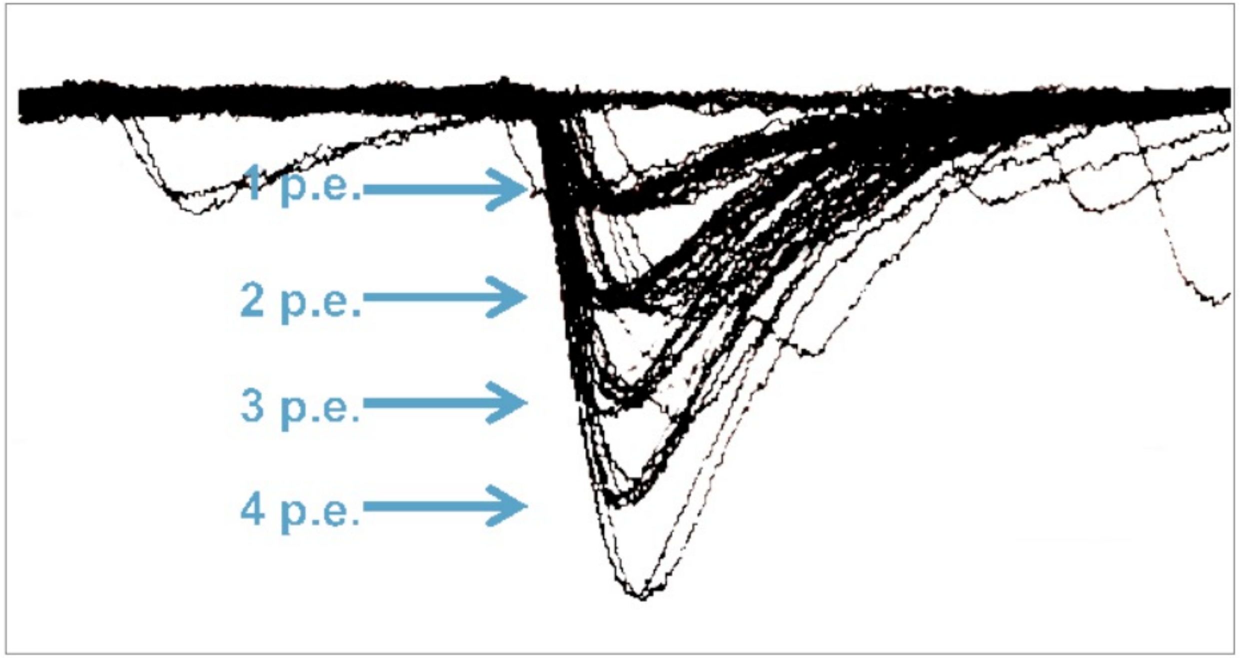
$$\text{Gain} = \frac{\text{avalanche\_charge}}{q} = \frac{V_{ov} \cdot (C_q + C_d)}{q}$$

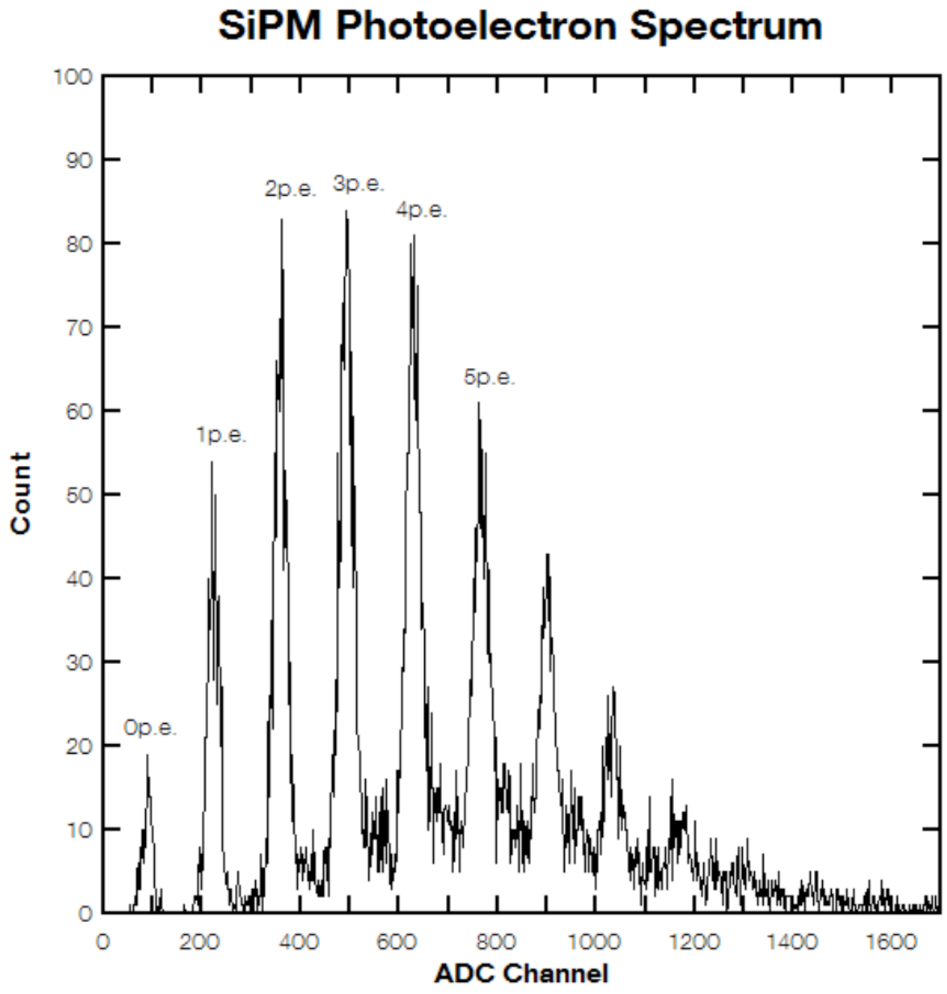
q=elementary charge



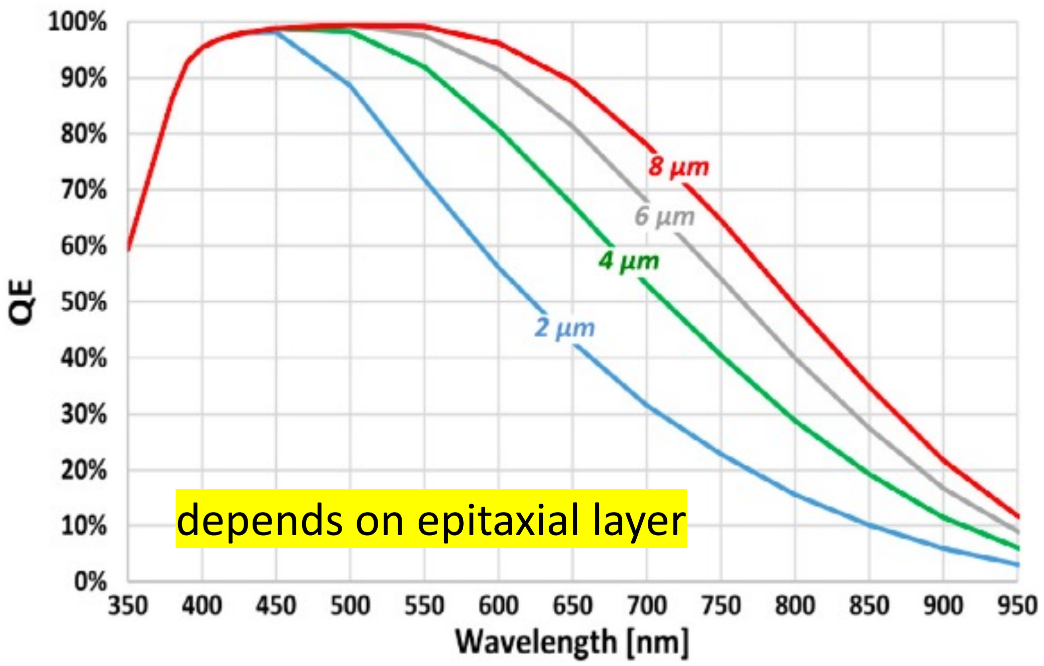
Note: with V_{over} at some volts,
Capacitances are typically O(fC)

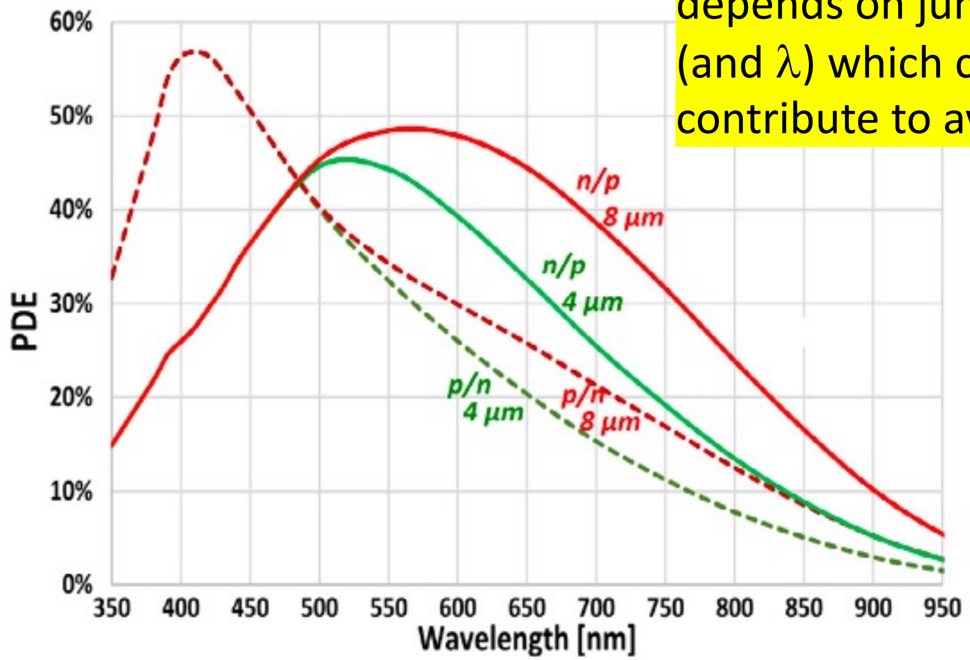
SiPM: “discrete” signals





SiPM: internal QE and PDE





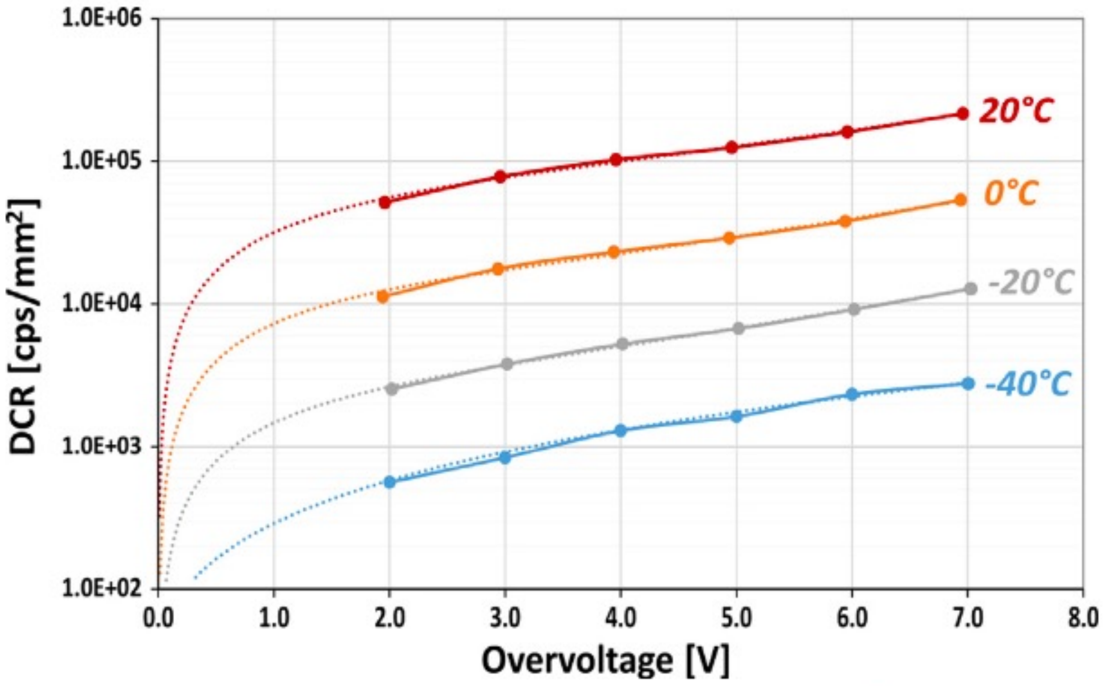
depends on junction type (and λ) which carriers contribute to avalanche

$$PDE(V_{OV}, \lambda) = QE(\lambda) \cdot P_T(V_{OV}, \lambda) \cdot FF_{eff}(V_{OV}, \lambda)$$

For the single SPAD FF is not part of QE, but it must be for the PDE of SIPM array!. For SPAD PDP is reported ("Photon Detection Probability")

PDE = (number of detected photons)/(number of photons reaching the detector)
QE=effectiveness to convert photon in an electron (include no reflection etc.)
P_T= avalanche trigger capability

SiPM DCR ("Dark Count Rate")

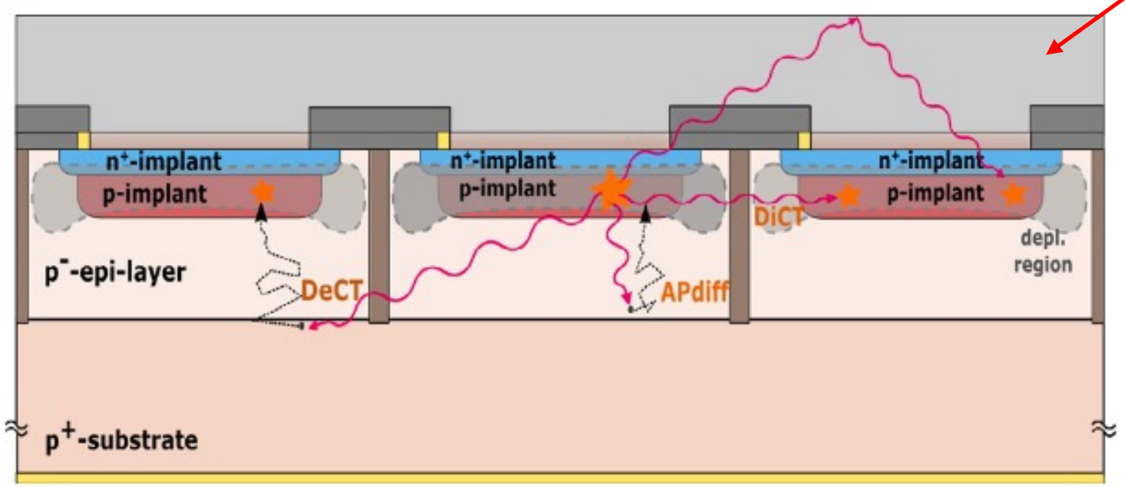


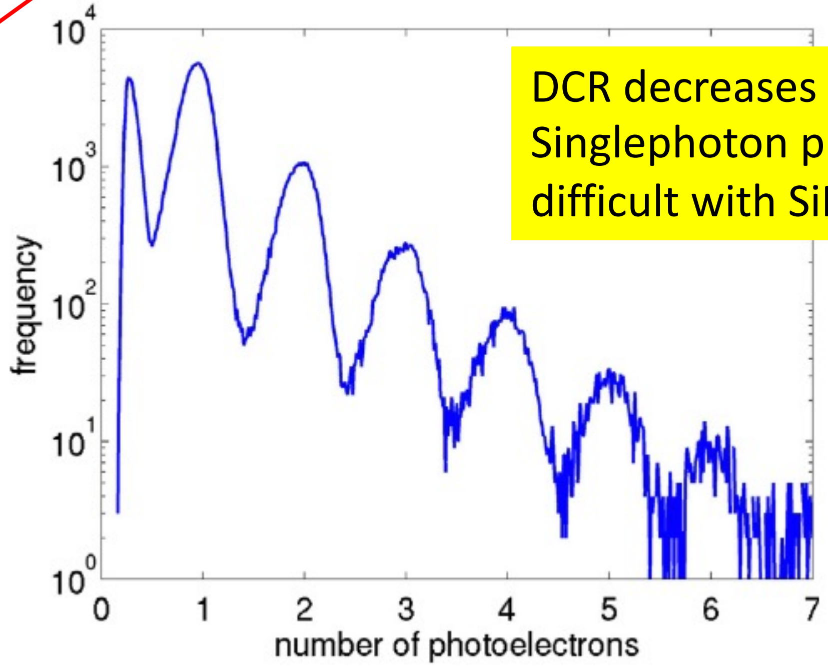
Reduction of DCR by a factor 2-2.5 every 10 degrees

Primary noise: avalanche triggered by thermally generated carriers or tunnelling in high-field region (depends on thicknes/purity of depleted layer)

Correlated noise: (after a primary event):

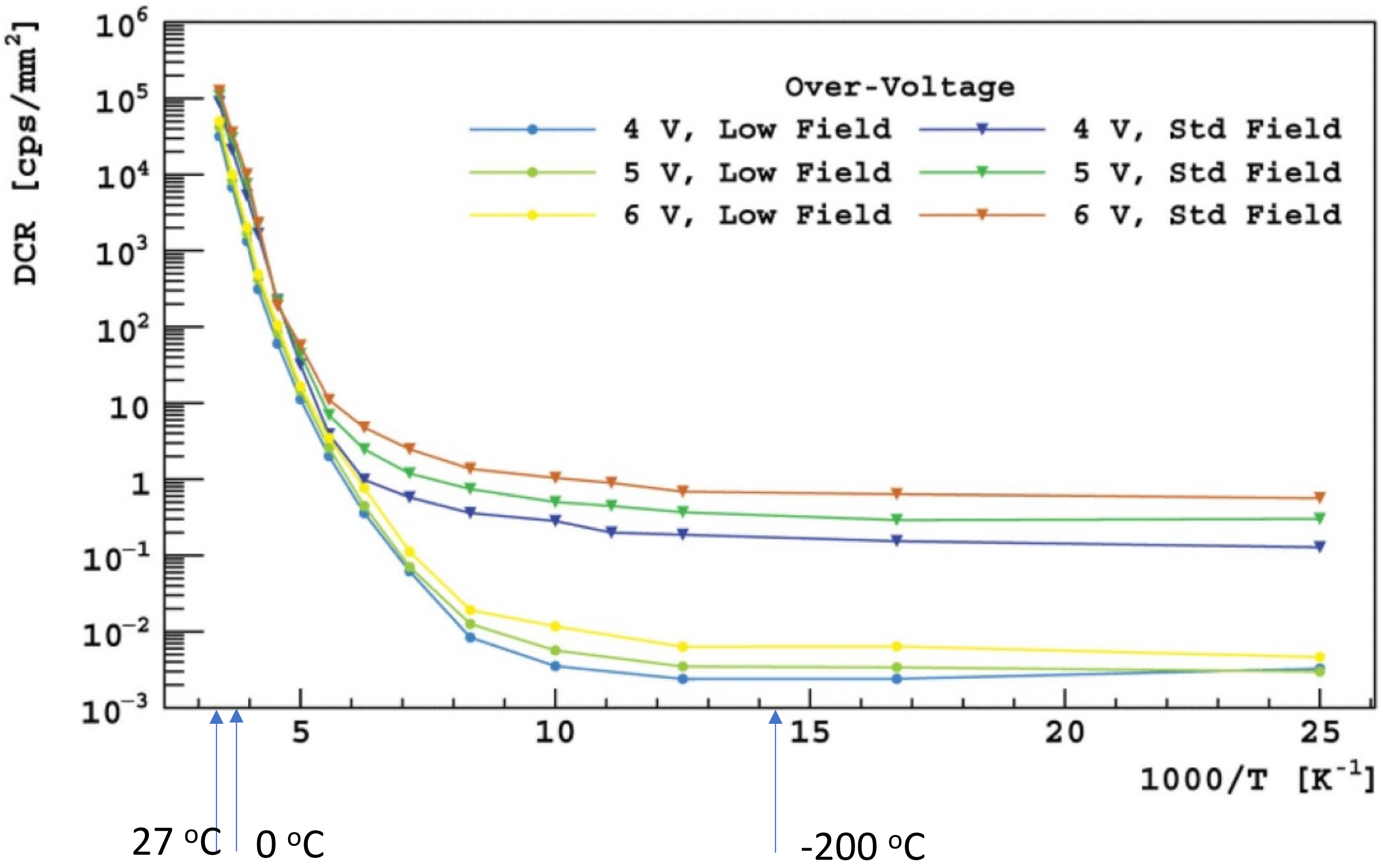
- Afterpulsing (same cell): due to carriers trapped in the depleted region and then released
- Optically induced cross-talk (in same or close SPAD)





DCR decreases with n_{phe}: Singlephoton physics more difficult with SiPM

SiPM: again on DCR

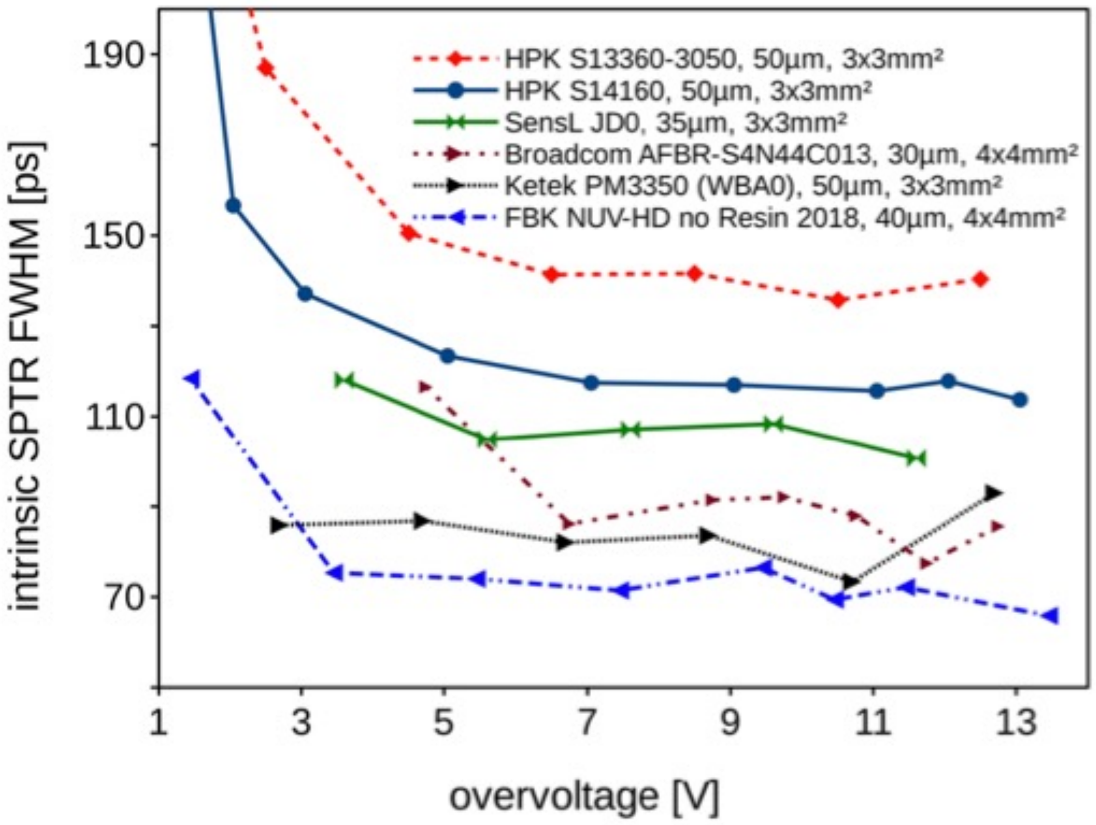


Exponential decrease of DCR stops at cryo temperatures

Remaining DCR is due to tunnelling effects and it is highly dependent on the electric field in the depleted region

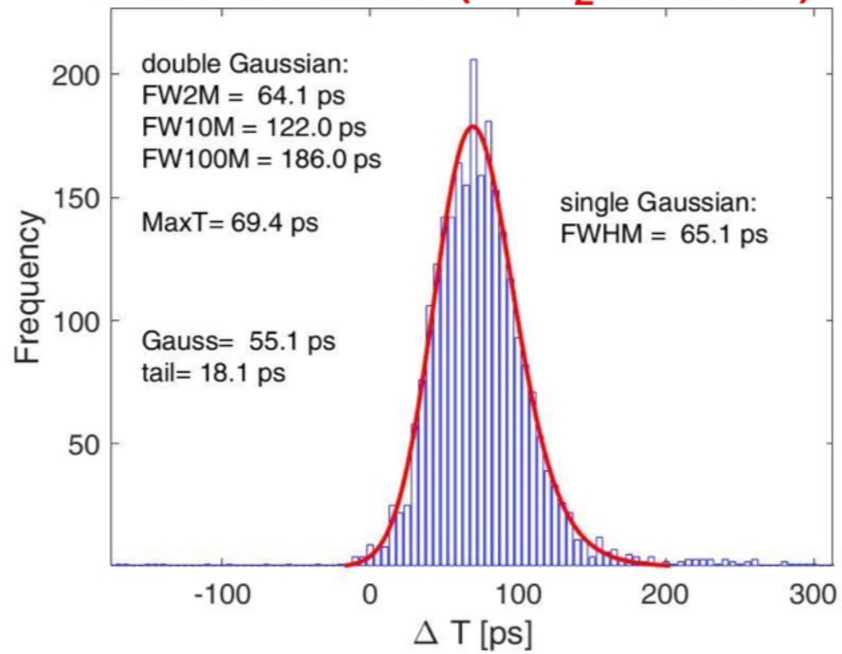
Cooling can play key role in operating SiPM at low DCR!

SiPM and timing resolution



S. Gundacker et al., Phys. Med. Biol. **65** (2020) 025001

SPTR FWHM (PbF_2 method)



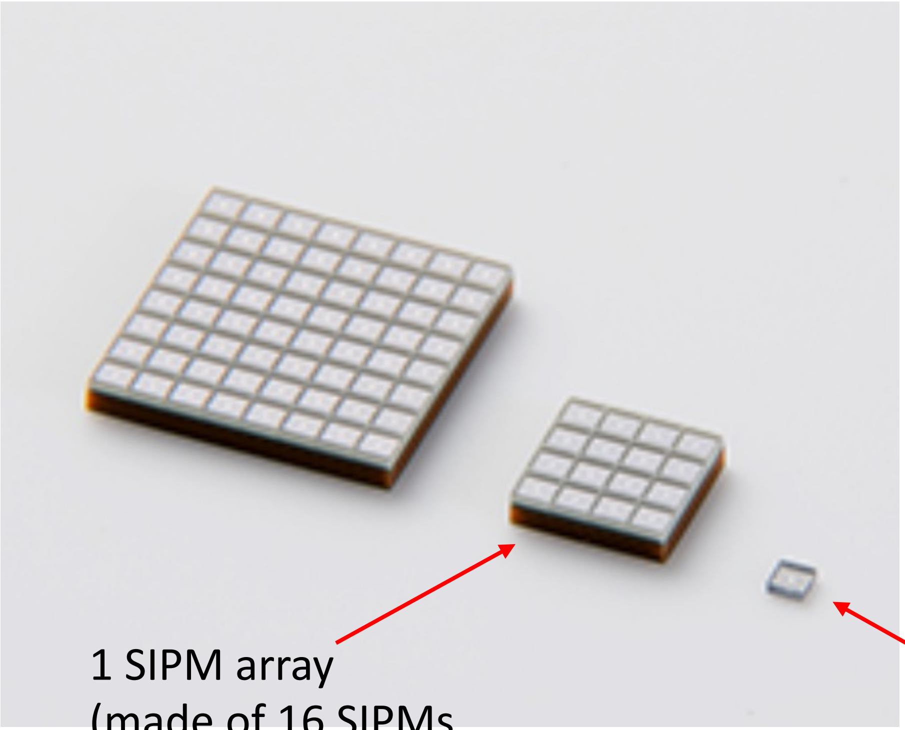
FBK CHK-HD

$$SPTR_{intrinsic} = \sqrt{65^2 - 47^2 - 21^2} = 39.6\ ps$$

S. Gundacker at FTM 2022 Worskhop

many effort in the context of TOF-PET (Positron-Emission Tomography) --> field rapidly evolving here!

SiPM: how they look like



1 SIPM array
(made of 16 SIPMs
each of them made of many SPADs…)

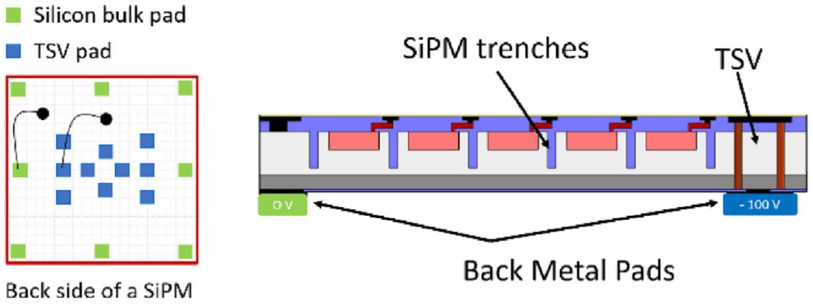
Let's check together a real datasheet from Hamamatsu here:
https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s13361-3050_series_kapd1054e.pdf

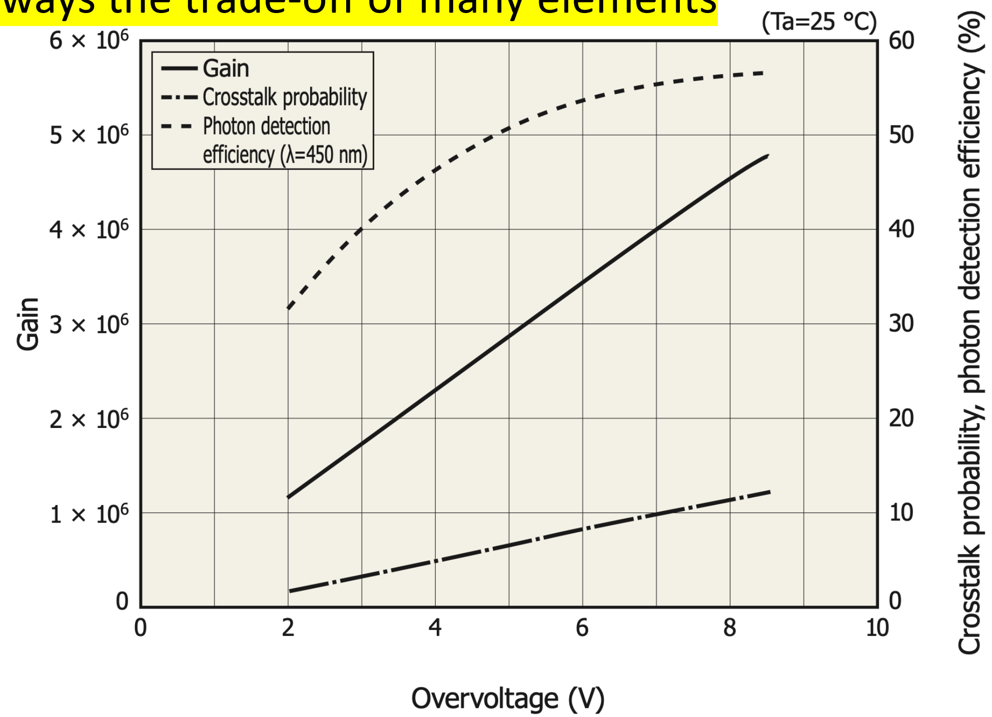
→ Note Hamamatsu calls the SiPMs "MPPC": Multi-Pixel Photon Counter

The choice of the operating conditions of the sensors in a real application will be always the trade-off of many elements

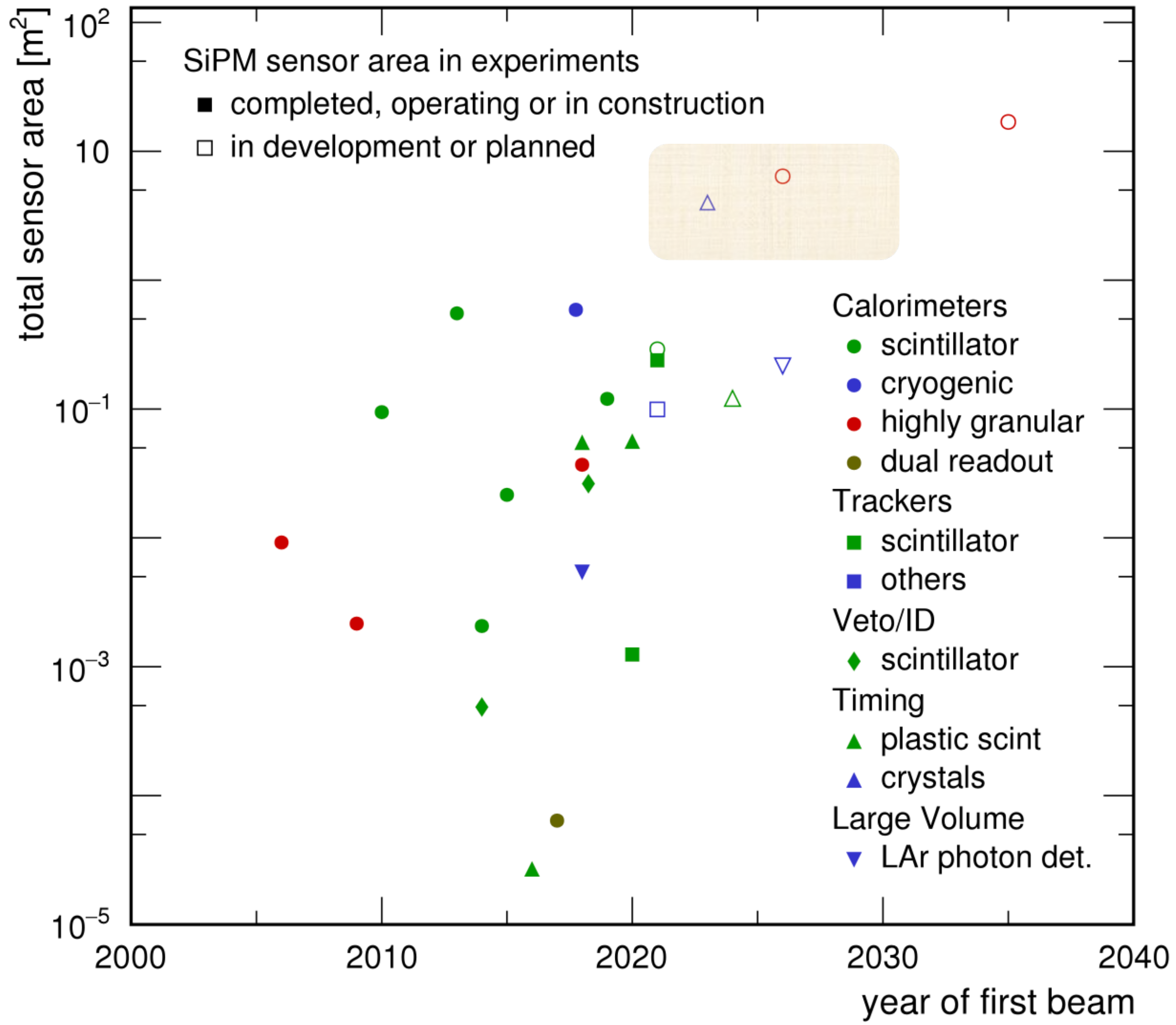
1 SIPM
(made of many SPADs)

(note on TSV technology: True Silicon Via: avoid wiring on the photosensitive area)





SiPM are now ubiquitous in HEP/NP



F. Simon, NIMA 926 (2019) 85-100

SiPM are naturally attractive for HEP/NP

- Small size
- High Photon-detection efficiency
- Cheap
- Insensitive to magnetic field
- High Gain

- ➢ Radiation tolerance
- ➢ Finite dynamic range (depending on cells)
- ➢ Temperature dependence of V_{bd}
- ➢ Dark Current Rate

Next frontier: SiPM O(1-10 m^2) area/detector

Here just focus on calorimetry and PID

SiPM readout for calorimetry: from CALICE to Hydra2

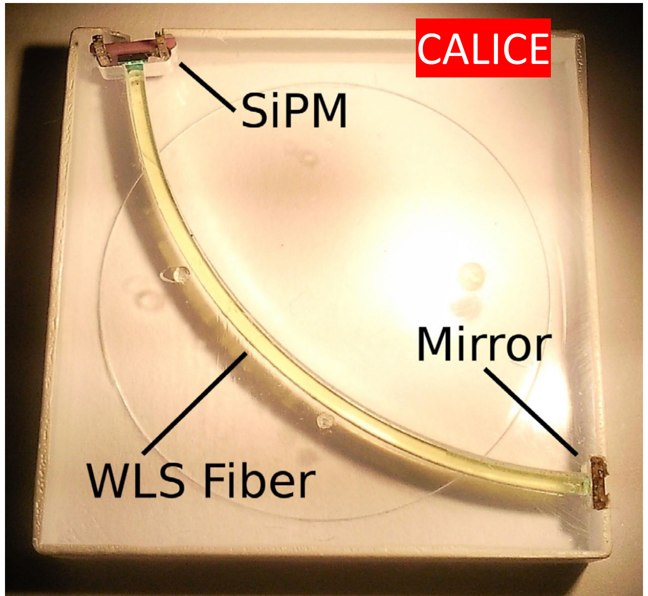
INFN Istituto Nazionale di Fisica Nucleare

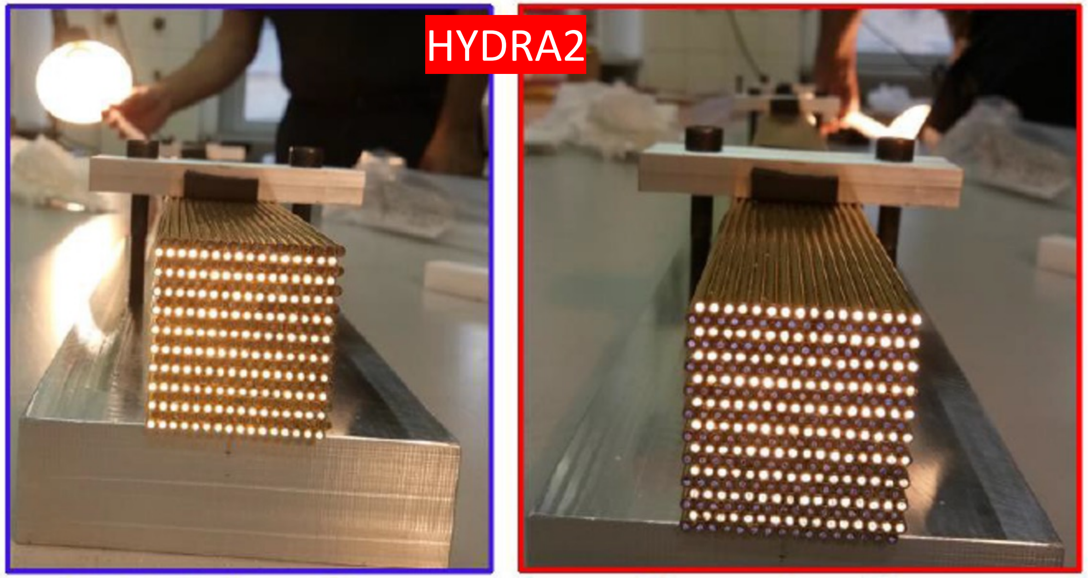
Most common application of SiPM → Readout of organic/inorganice scintillators → calorimeters
Geiger-mode + finite density → inherent saturation → compensation techniques to recover linearity

Detector	Year	Info	SiPM	SPAD μm
CALICE AHCAL	2004-2006	Hadron calo. 7608 phtosensors "Demonstrator" WLS embedded in the tile. Coupling fiber-SiPM with air gap	MEPHi/CPTA 1x1 mm^2	32
T2K	2010	ECAL (and othe sub-systems; tracker, p0 detector, muon tracker) Track and shower resolution 1 ns https://arxiv.org/pdf/1308.3445.pdf	HPK S10362 1.3x1.3 mm^2	50
DREAM	2018	Dual Readout calorimeter "Demonstrator" // RD52 Cerenkov light yield measured twice w.r.t "PMT versoin" https://doi.org/10.1016/j.nima.2018.05.016	HPK S13615 1x1 mm^2	25
HYDRA2	2023+	Dual Readout calorimeter "Demonstrator". // AIDAInnova Recent development with hgh number of channels	HPK S16676 1x1 mm^2	10 15

*Take home message

- From pioneering times to baseline choice for future sophisticated calorimeter
- HPK sets the standard (and customises for HEP/NP)





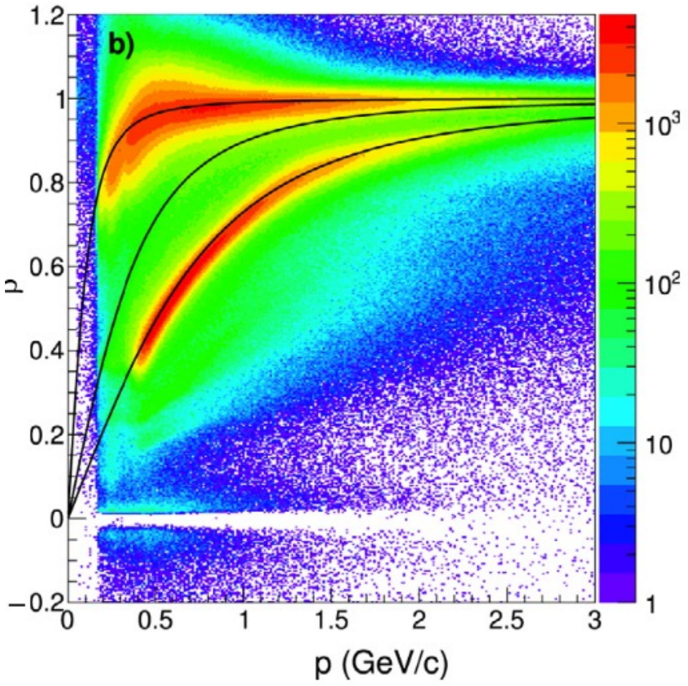
scintillation fibers   Cherenkov fibers

- 9 modules made of 16 x 20 capillaries
- capillaries (brass): 2 mm outer diameter and 1.1 mm inner diameter
- 81920 fibers (currently 10000 equipped with SiPM)

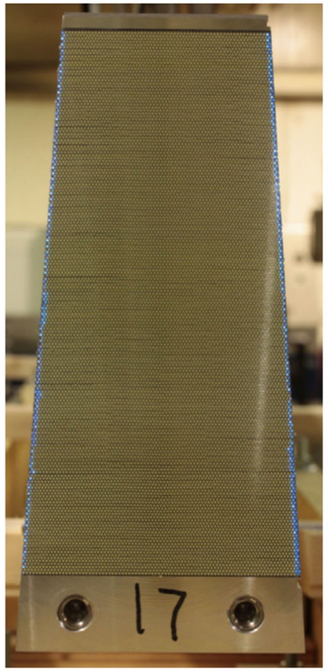
Calorimeters with SiPM readout: GlueX example

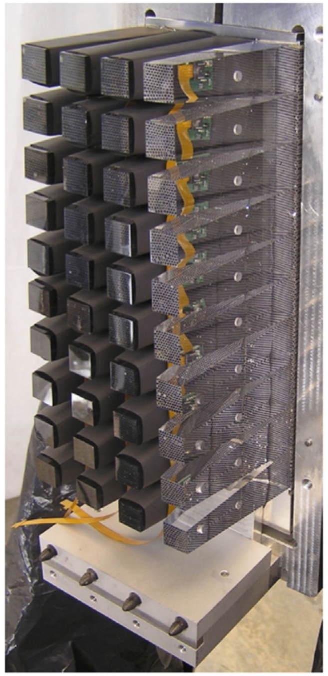
@Jefferson Lab / USA

- 2013 → one of early SiPM adopters!
- barrel ECAL: photons from 50 MeV to several GeV / sampling calorimeter
- 3840 SiPM installed: 13x13 mm^2 / 16 channel 4x4 array
- Hamamatsu S12045(X) (SPAD 50x50 mm^2)
- Energy resolution $\sigma_E/E = 5.2\%/\sqrt{E(\mathrm{GeV})} \oplus 3.6\%$ comparable to KLOE (PMT based)



PID detector (TOF) given SiPM time resolution (150 ps)

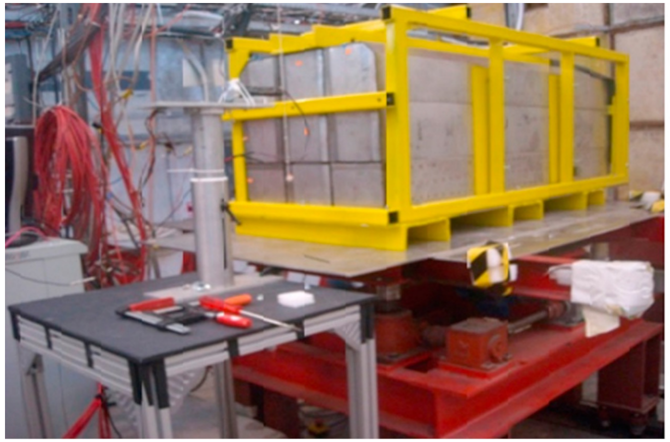


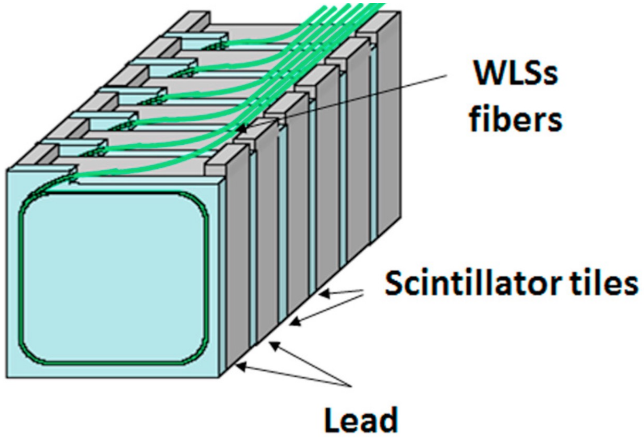


Nuclear Inst. and Methods in Physics Research, A 896 (2018) 24–42

Calorimeters with SiPM readout: example

@GSI-FAIR/ Germany





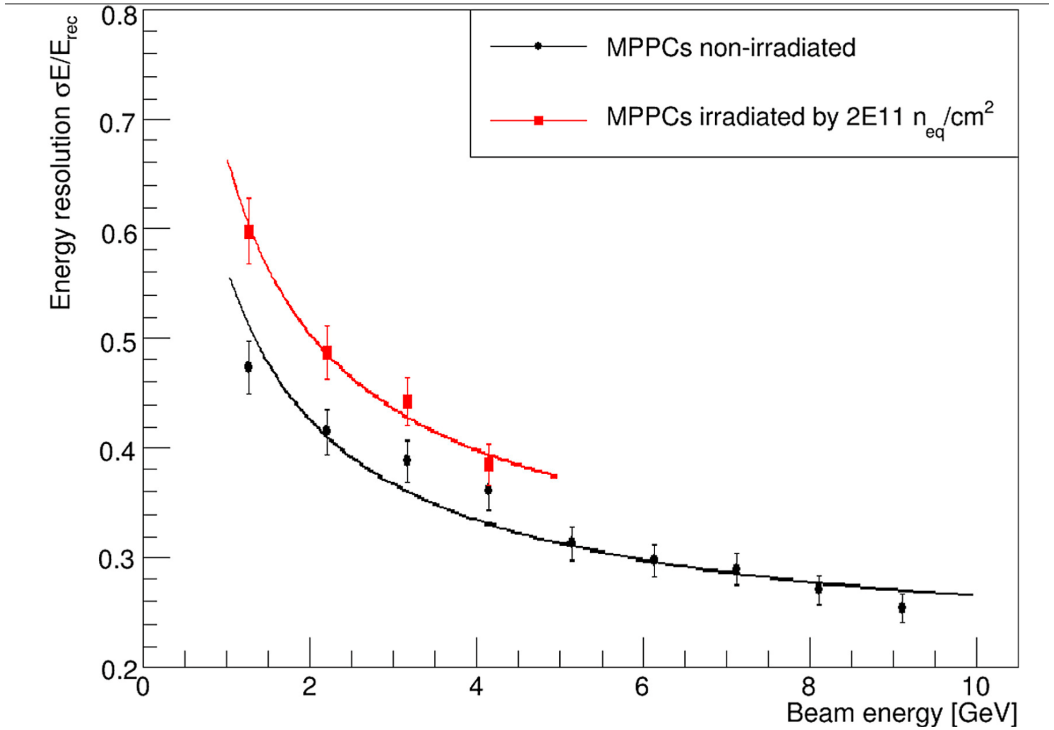
CBM Projectile Spectator Detector (forward hadron calorimeter)
N. Karpushkin et al., NIMA 936 (2019) 156
https://doi-org.ezproxy.cern.ch/10.1016/j.nima.2018.10.054

60 lead/scintillator layers → WLS → SiPM readout
SiPM readout: MPPCs S12572-010P

radiation damage tested for SiPM

*Take home message

DCR increase normally manageable,
But impact on energy resolution must be studied



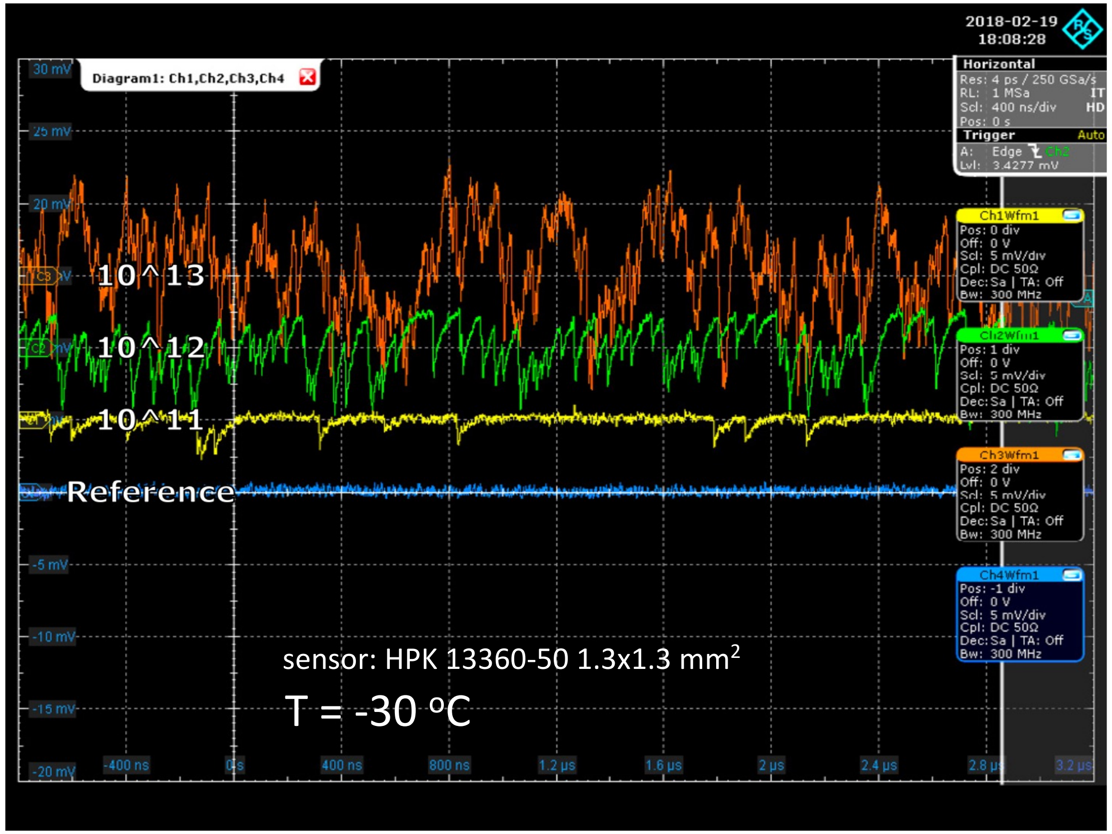
Intermezzo: what is SiPM radiation damage?

During last 10 years growing studies/ literature on SiPM radiation damage, see review from
E. Garutti and Y. Musienko, NIMA 926 (2019) 69

Up to 10^{11} 1-MeV n_{eq} /cm^2 radiation damages increase currents and DCR (and affects V_{bd}) **but the baseline is still there** (with proper cooling)

- For a calorimeter: how the damaged baseline spoils energy resolution and how affect efficiency
- For a RICH: can we maintain single photon detection, can we keep DCR “under control” to still get rings?

M. Calvi et al., NIMA 922 (2019) 243



Intermezzo: how mitigate the radiation damage?

INFN
Istituto Nazionale di Fisica Nucleare

"DCR decreases by a factor 2-2.5 every 10 degrees"

annealing

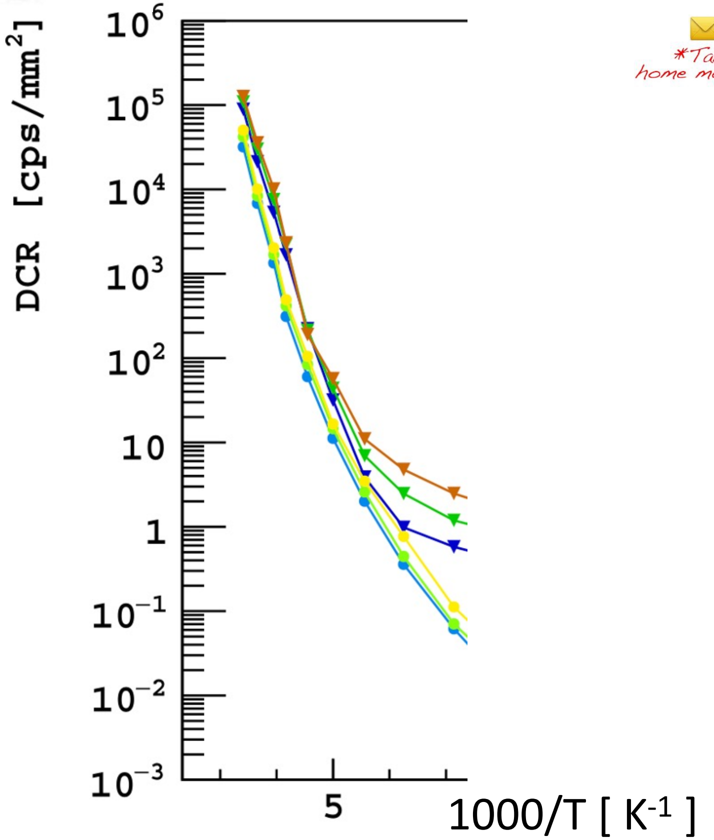
"DCR decreases by a **factor 20** after an annealing cycle up to 175 °C"

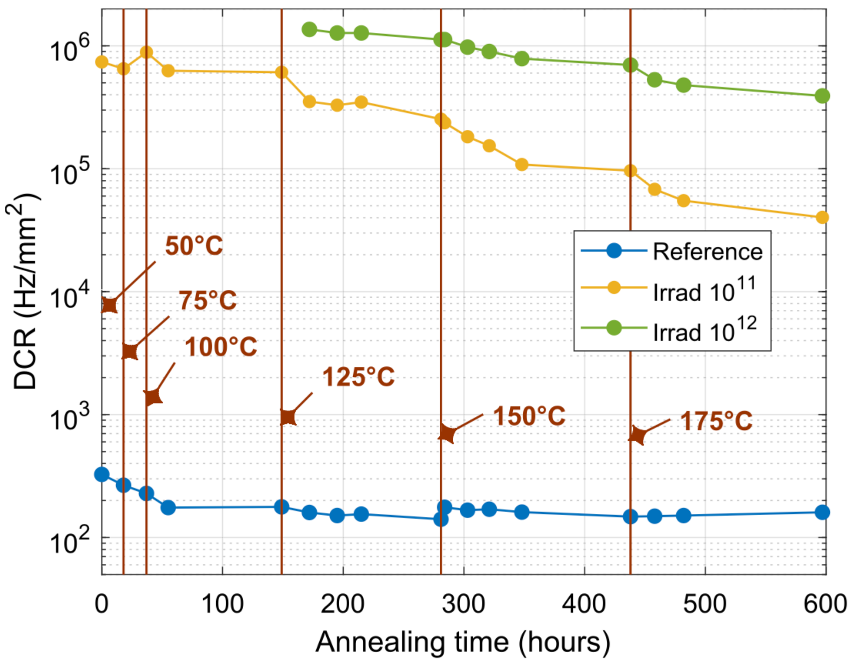
timing

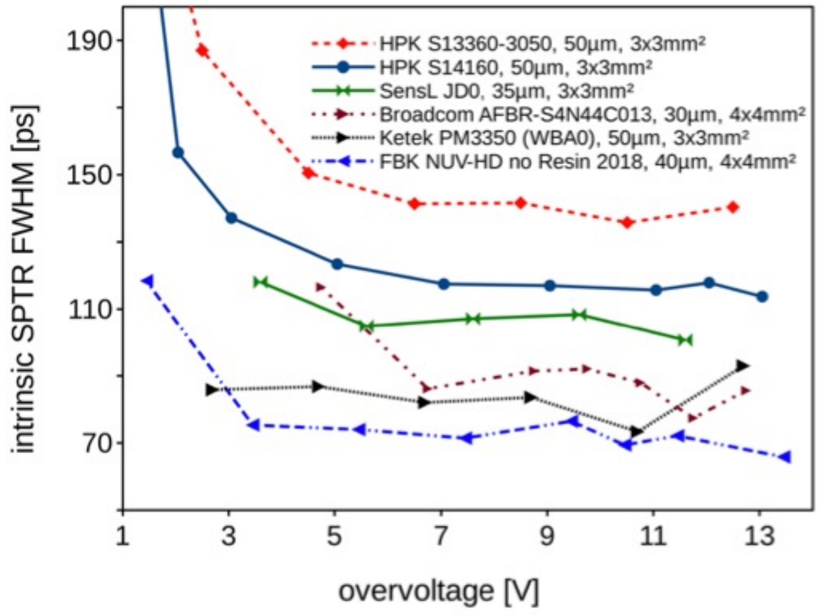
- Timing resolution below 100 ps are nowadays achieved by SiPM
- A 3σ cut based on interaction time can reduce DCR ("time shutter on front-end electronics")

*Take home message

How, how often and where to anneal depend on the application







Acerbi F. et al., IEEE Trans. On El. Devices 64 (2017) 521

M. Calvi et al., NIMA 922 (2019) 243

S. Gundacker et al., Phys. Med. Biol. **65** (2020) 025001

*Take home message

cooling is critical in SIPM-based readout

calorimeters

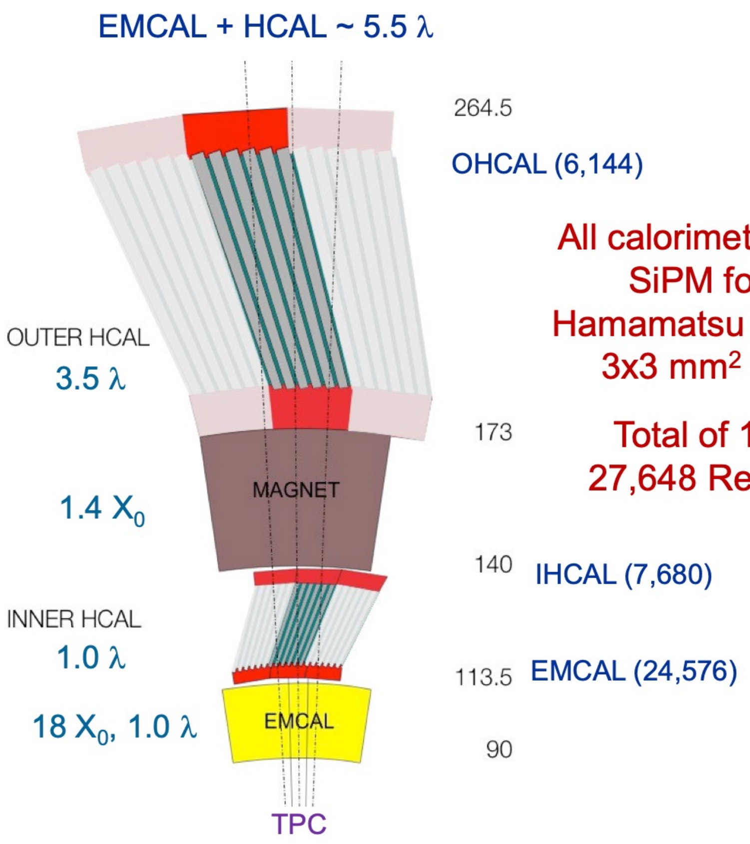
sPHENIX will operate during next 3 years!

EMCAL – Tungsten SciFi SPACAL

- ± 1.1 in η, 2π in ϕ
- $\Delta\eta \times \Delta\varphi \approx 0.025 \times 0.025$
- 96x256 = 24576 readout channels
- $\sigma_E/E < 15\%/\sqrt{E}$

HCAL – Steel plates + scintillating tiles with WLS fiber readout

- Plates oriented parallel to beam
- Iron serves as flux return
- Plates are tilted to avoid channeling
- Two longitudinal sections (~ 4.5 λ)
  - Inner HCAL inside magnet
  - Outer HCAL outside magnet
- $\Delta\eta \times \Delta\varphi \approx 0.1 \times 0.1$
- 2x24x64 = 3072 readout channels
- $\sigma_E/E < 100\%/\sqrt{E}$ (single particle)



All calorimeters use same SiPM for readout
Hamamatsu S12572-015P
3x3 mm^2 15 μm pixel

Total of 112,128 SiPMs
27,648 Readout Channels

@BNL/ USA

- S12572 selected before trench technology developed
- 15 μm to have large dynamics
- O(1) m^2 total SiPM area

Courtesy: C. Woody (BNL) see also this link

SiPM-calorimeters experience

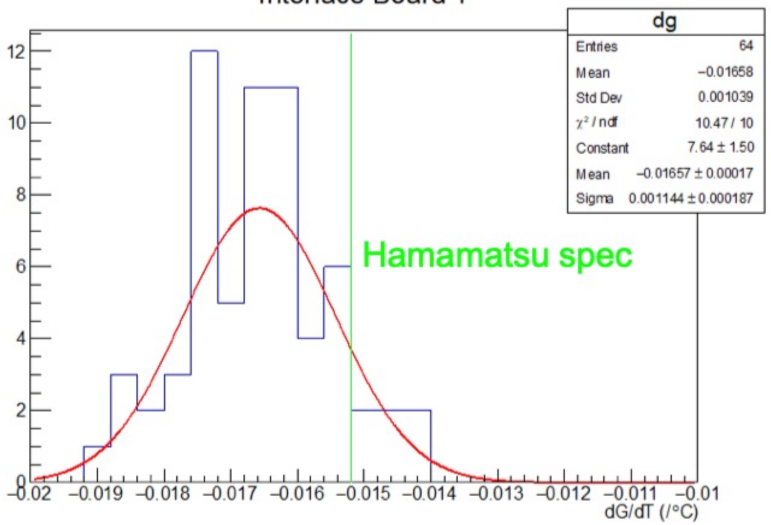
Important lessons learned by sPHENIX on:

- temperature dependence → cooling system
- radiation damage → small slow long term recovery at RT
- fluence expected 10^{11} n_{eq}/cm^2

EMCAL Cooling System

SIPM Loop
Sector 1

Gain Temperature Coeff dG/T (%/°C)



in SiPM business cooling is not just about DCR decrease or mitigation of radiation damage

SiPM calorimeter R&D

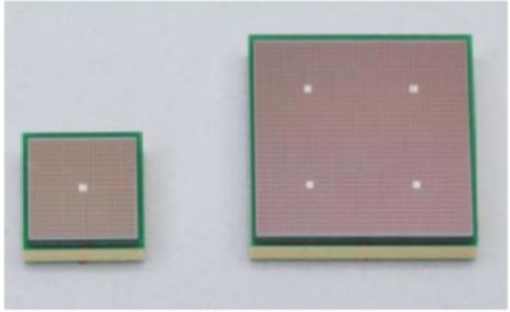
@BNL/ USA since 2030

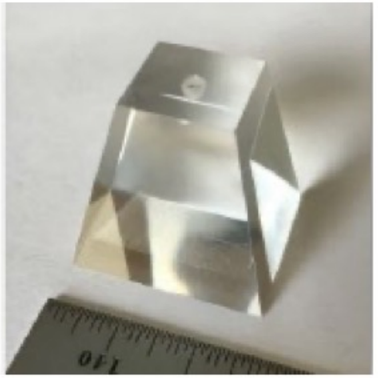
Some annotations SiPM-related:

> re-use of sPHENIX HCAL
Improve photocatode coverage (improve energy resolution) → HPK 13660 6x6 mm^2

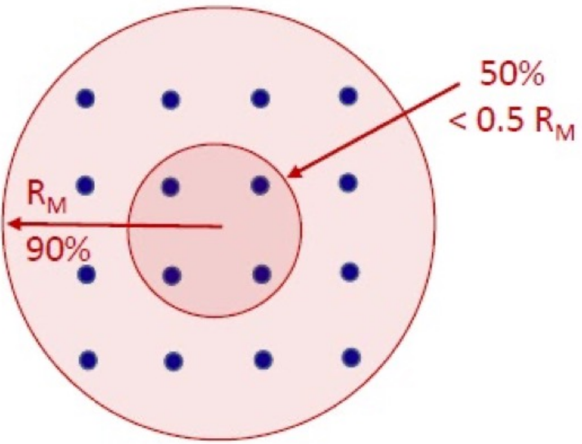
- Keep existing light guides/replace 2x2 array of 3x3 mm SiPMs with four 6x6 mm^2
- Remove or cut down existing light guides and cover entire readout end of block with a 6x6 array of 6x6 mm^2 SiPMs.

Hamamatsu S13360 6x6 mm^2
SiPM with TSVs (50 μm pixels)





"Large" area SiPM might improve energy resolution (if radiation damage "limited")



> Pb-Shashlik ECAL (forward)

- *each fiber read-out individually:* shower position determination even within a Moliere radius.
- A compact shashlik may also offer the possibility of improving the position dependence due to the short light path to the WLS fibers

SiPM low cost really opens up detector performance improvements

PID

Three broad categories here for SiPM use:

"similar" to calorimetry

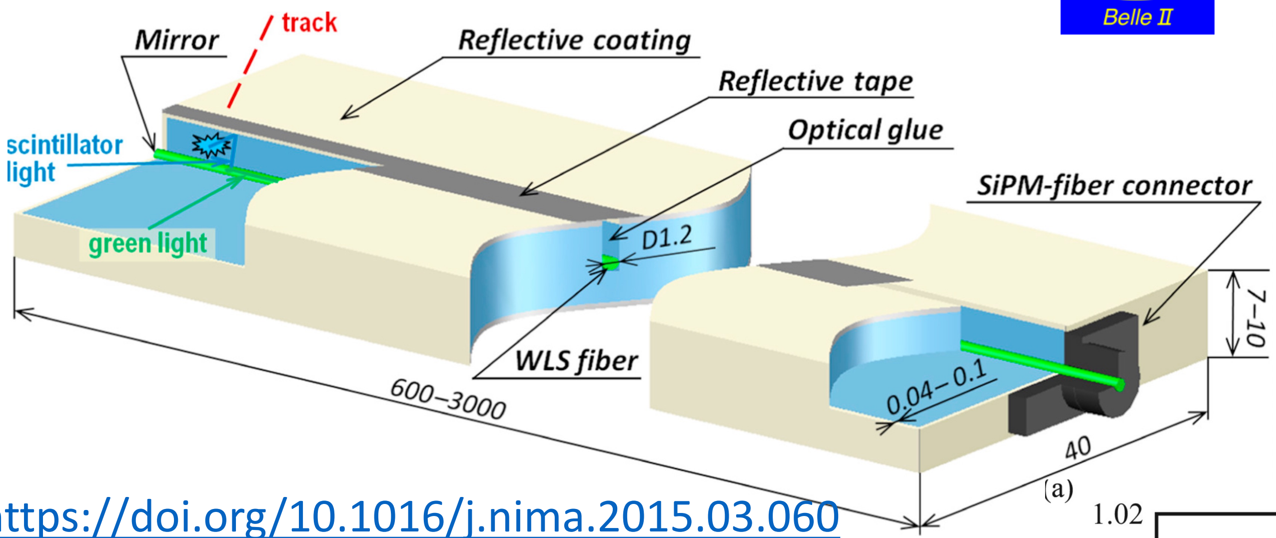
1. plastic-scintillator based (charged particle/showers) → scintillation light
2. Detection of Cerenkov light (RICH)
3. Time-of-flight detectors

Not realized so far, it could be at reach within 7-10 years

Examples of PID/veto with scintillation light

@KEKB/Japan

EKLM detector @ Belle II for K_L and muon



https://doi.org/10.1016/j.nima.2015.03.060

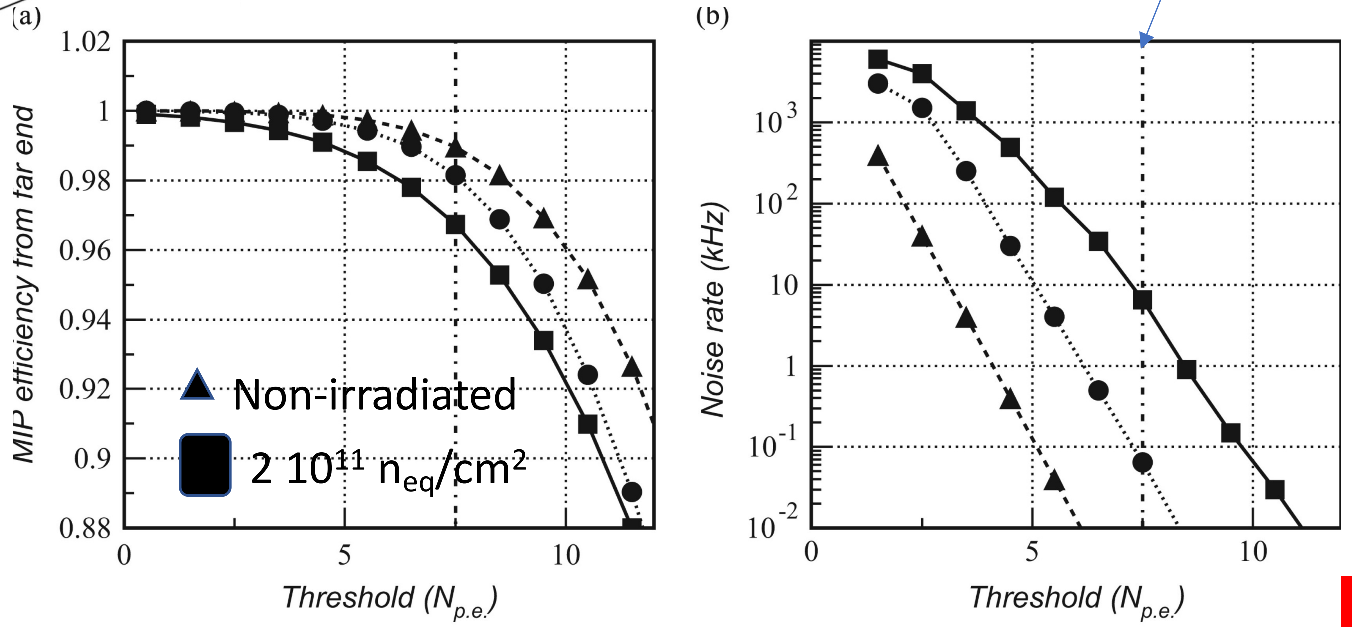
- Alternating layers of active scintillator and 4.7 cm thick iron plates
- SiPM choice strategic (no PMT due to magnetic field)
- CPTA / Hamamatsu choice done based on radiation tolerance studies
- **The difference between the Hamamatsu and CPTA mainly due to different thicknesses of the sensitive zone and the difference in manufacturing details (purity of the raw materials and also of the SiPM surface [→ impact on "starting dark noise"]**

3.9 interaction lenghth → K^0_L can shower hadronically → muon separation

Note RPC were replaced due to "fake showers" generated by neutrons. DCR increase due to neutrons in SiPM under control!

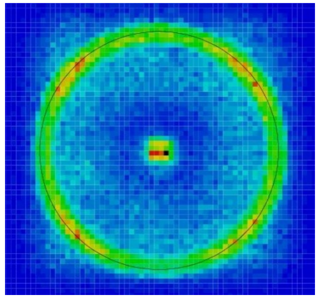
ALICE 3 is planning a Muon-ID scint+SiPM based

Operating threshold



RICH with SiPM based readout?

So far not realized
Pioneering work during Belle II Upgrade studies
P. Križan et al. NIM A594 (2008) 13
https://doi.org/10.1016/j.nima.2008.05.040
https://doi.org/10.1016/j.nima.2008.07.013



CAVEAT:
pioneering work for BelleII was done in 2010 with (now obsolete, noisy and out-of-market) Hamamatsu MPPC S10362-11-100P

Main reference: a recent (2020) review exactly on this topic:

https://doi.org/10.1016/j.nima.2020.163804
S. Korpar, P. Križan. "Solid state single photon sensors for the RICH application"

As potential detectors were listed here:

- HELIX
- LHCb RICH1 Upgrade 2
- RICH for a SuperCharm-Tau factory (21 m^2)
- BELLE II ARICH
- ePIC RICH @EIC

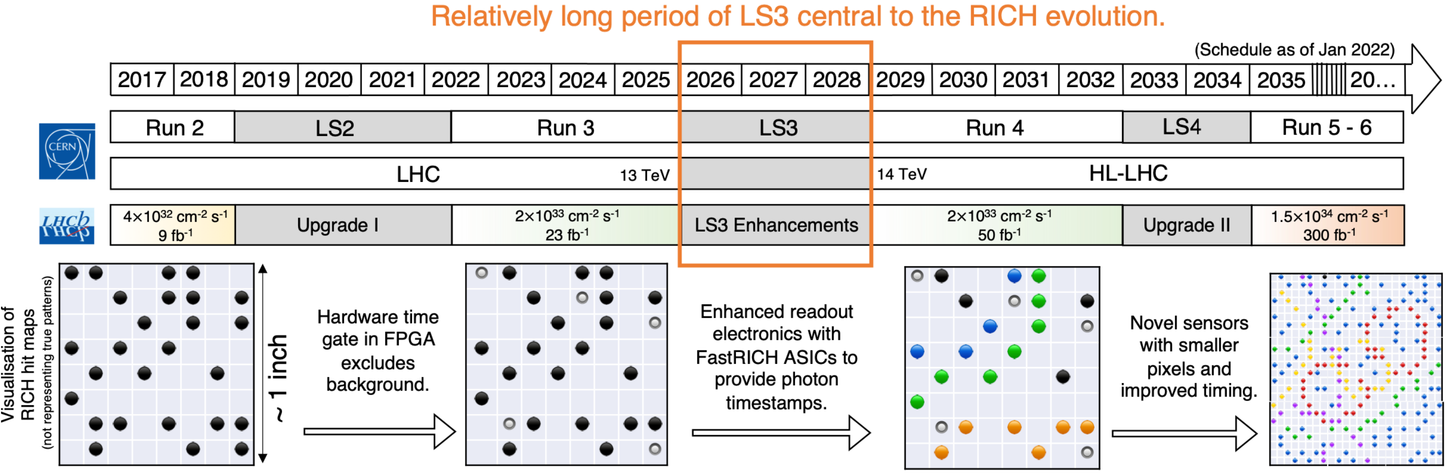
7. Summary

Semiconductor sensors for single photons, in particular SiPMs, are a novel device for RICH. Their advantages, operation in the magnetic field, high quantum efficiency, low supply voltage, fast response, flexible granularity, make them an almost ideal sensor for ring imaging Cherenkov detectors. The main challenge, a high occupancy due to dark counts, can be overcome by a narrow time window and by using light collecting elements to increase the ratio of the light collection area and the SiPM sensor area. The remaining issue for operation in experimental environments with high radiation exposure, in particular by neutrons, is under intense study for the next generation of experiments.

LHCb RICH plans

Evolution of the RICH photon detector

@CERN/Switzerland



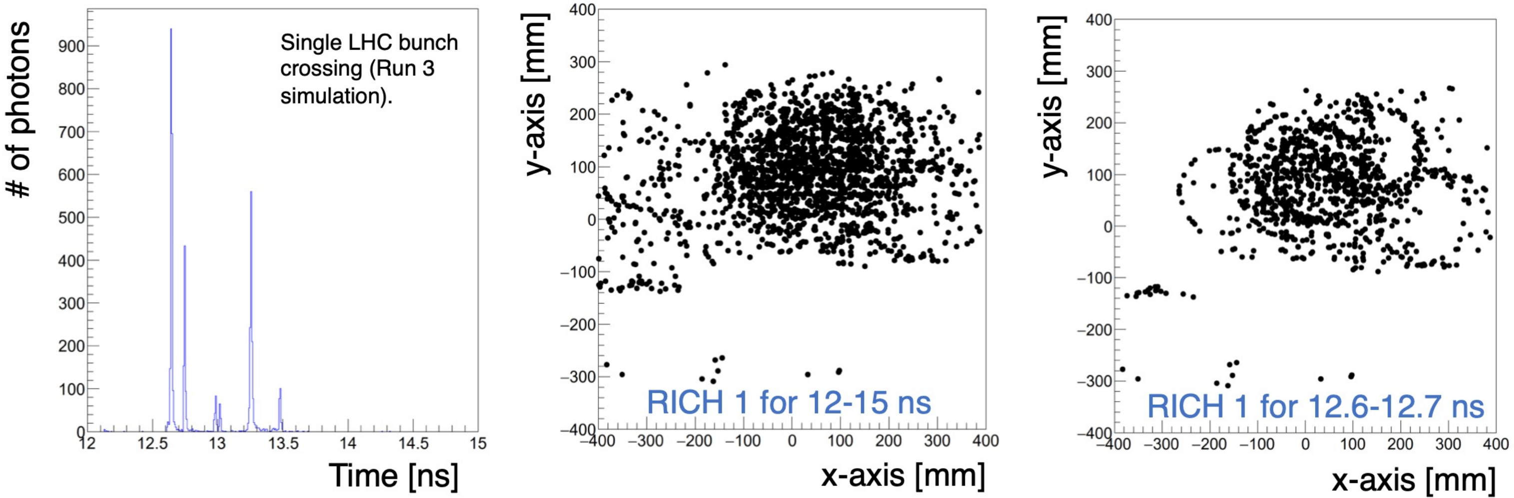
As photosensors in RUN5 @ LHCb
SiPM: R. Cardinale @RICH2022
LAPPD: F. Oliva @RICH2022
are being considered

- LS3 / Run 4 : focus on **FastRICH** readout electronics with fast timing and wide input dynamic range.
- LS4 / Run 5 : focus on **sensor technology**. Fast-timing is essential for the luminosity challenge after Upgrade II. [Ta

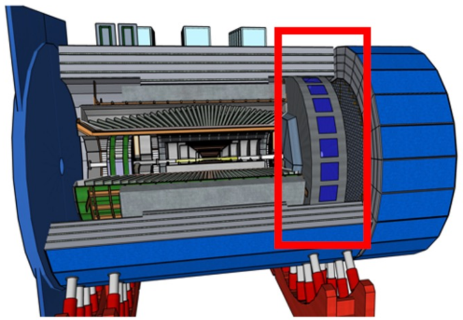
*Take home message

Fast switching electronics will be key for RICH SiPM based readout

To reduce background and improve PID, need to accurately predict **when** the photons from a given track ought to arrive.



dRICH @ePIC



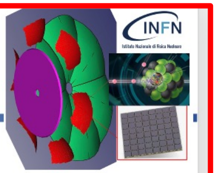
@BNL/USA

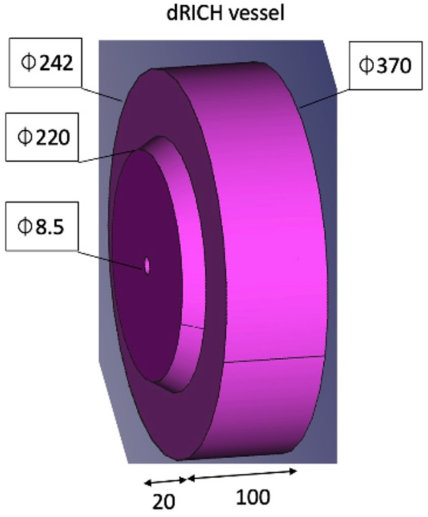
- radiators: Aerogel (n=1.02)/ Gas (n=1.0008)
- 3 m^2 area, 3x3 mm^2 pixel

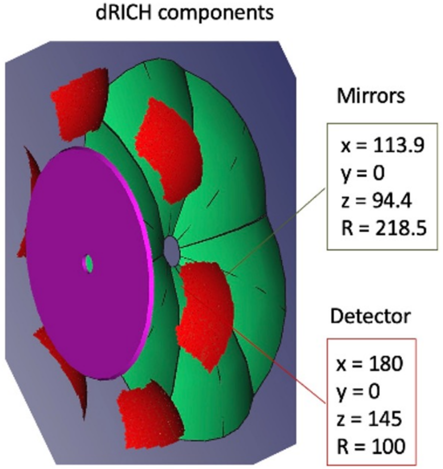
inside magnetic field (~ 1 T)
SIPM as baseline sensor

PA @ CPAD Workshop 2022

A SiPM readout for a RICH detector?







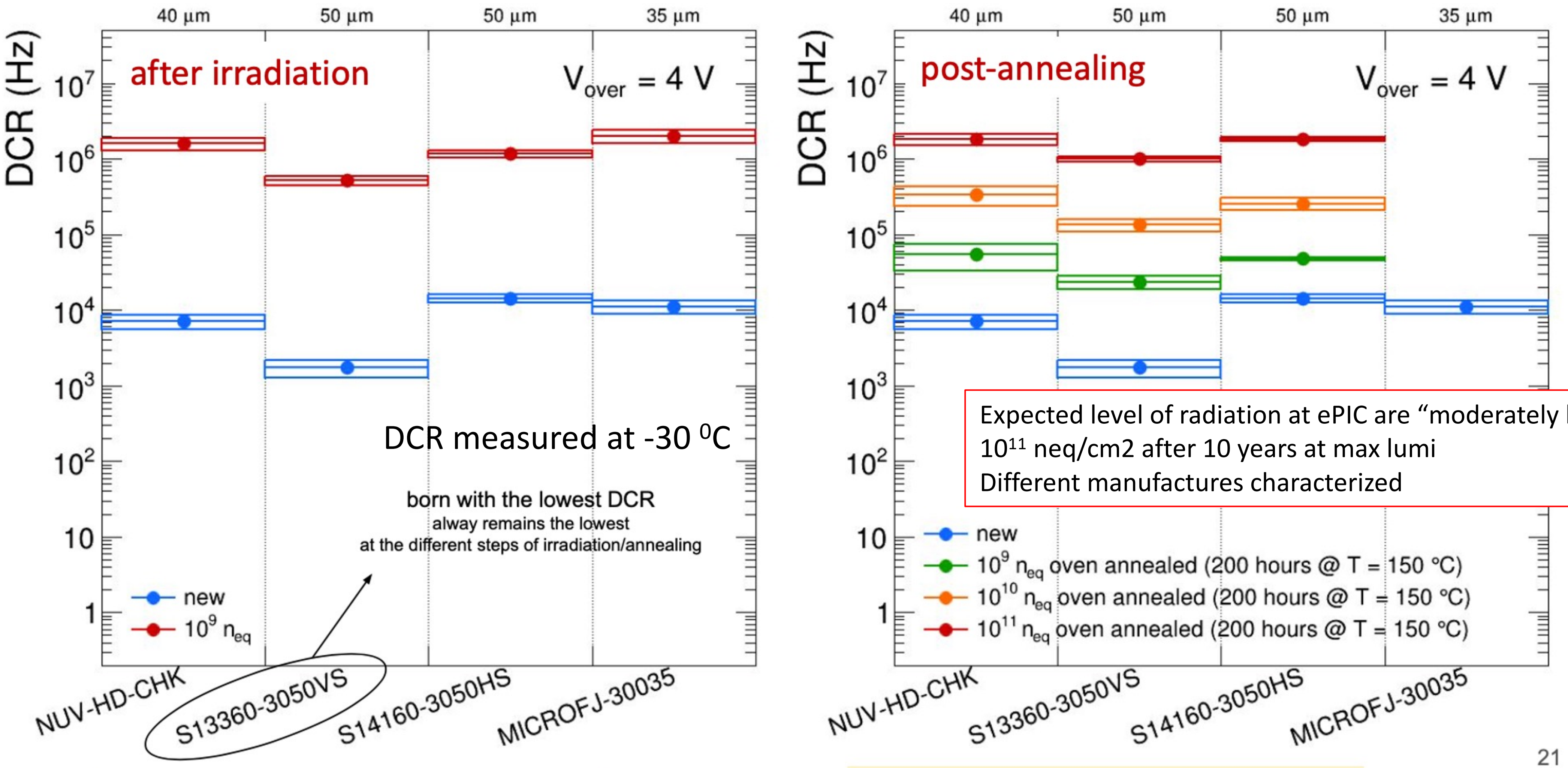
Silicon photomultipliers

✓ Insensitive to magnetic field
✓ Cheap / Integrated arrays
✓ Time resolution within requirements (< 200 ps RMS)
✓ Commercially available

? Single Photon resolution needed!
? DCR vs temperature → cooling
? Not radiation tolerant: DCR increases!

Our R&D: evaluate radiation tolerance and mitigation procedures (annealing)
→ test large O(10-100) samples of different commercial (HPK/OnSemi) and prototypes (FBK)
→ establish annealing protocol, evaluate DCR after repeated annealing cycles
→ characterize sensors and test them on beam conditions
→ use/test realistic readout with ALCOR ASIC

dRICH SiPM R&D



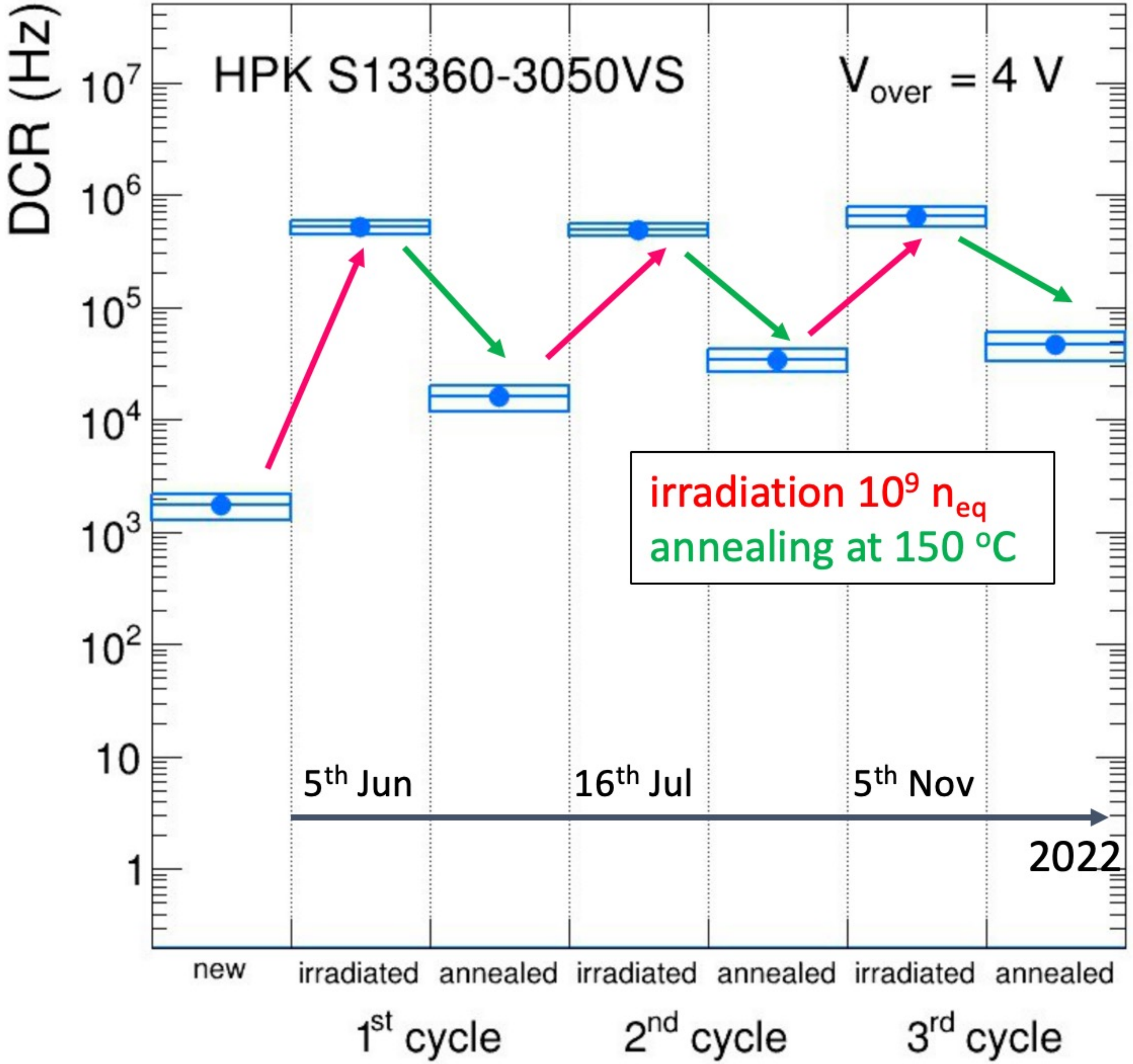
Expected level of radiation at ePIC are “moderately hostile”
10^{11} neq/cm2 after 10 years at max lumi
Different manufactures characterized

O(100) DCR increase after 10^{11} n_{eq}

O(10) DCR recovery post-annealing

More details in: R. Preghenella @ RICH2022

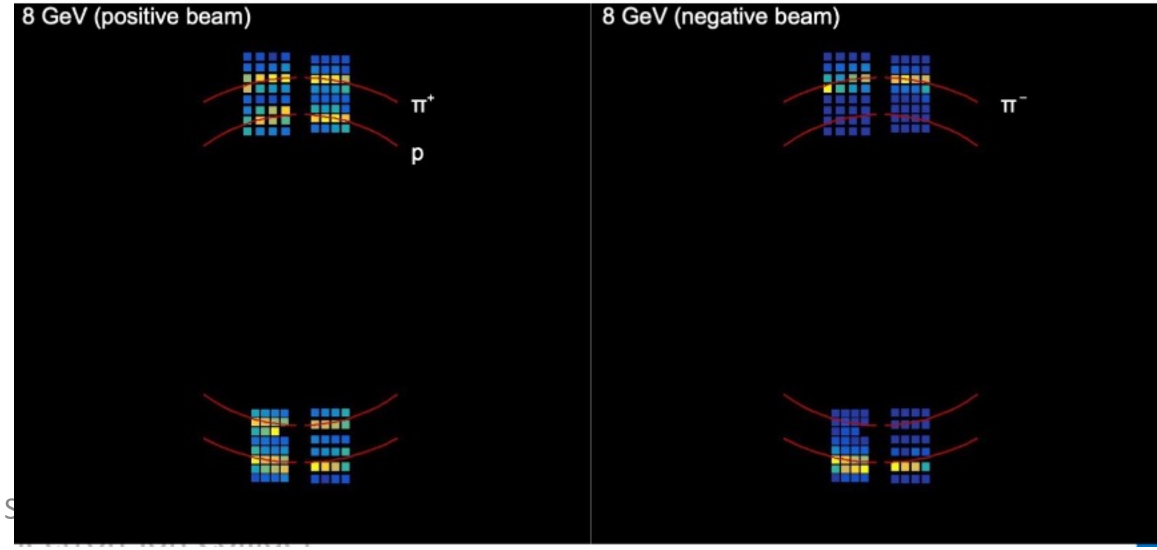
dRICH SiPM R&D



Novelty here:

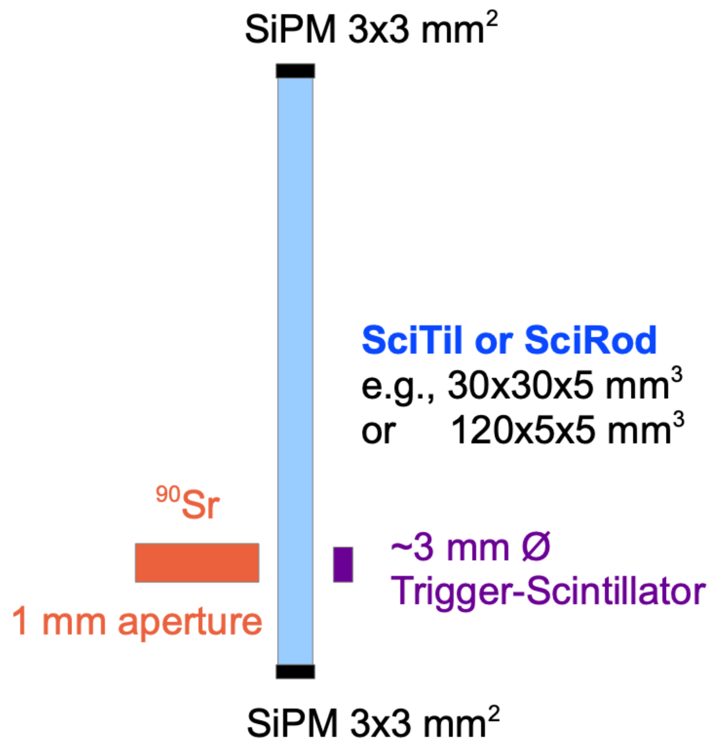
- test reproducibility of repeated irradiated/annealing cycles on the same sensors.
- each shot is 10^9 n_{eq} (remember: 0.2/1 year EIC at max lumi)
- extract parameters (sensor and V_{over} specific!) to shape annealing cycles in the experiment
- Ring structures detected correctly at test beam with (irradiated + annealed) sensors

no show stoppers so-far. Annealing "in-situ" with full-fledged prototype is next step!



TOF SiPM based readout: panda example

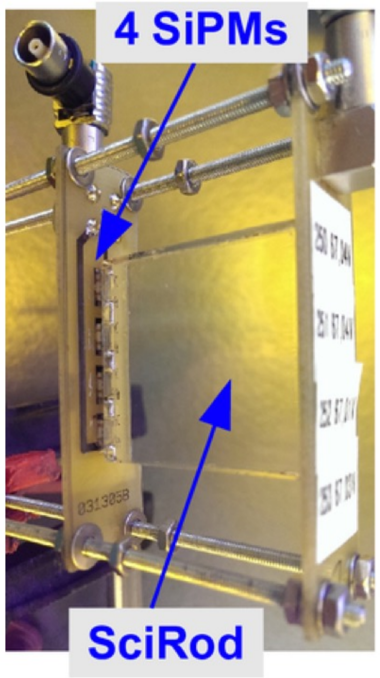
Istituto Nazionale di Fisica Nucleare

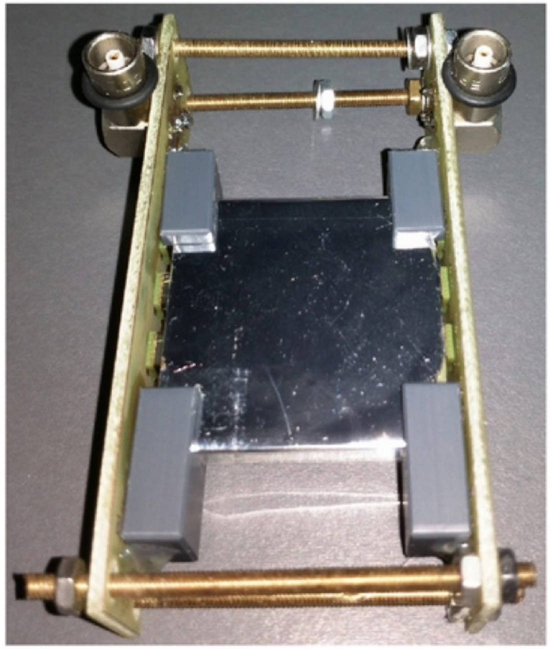


Scintillator light → SIPM

M. Böhm et al 2016 JINST 11 C05018
Hamamatsu S12652-050C MPPC
KETEK PM3350TP-SB0

Several optimization in design reported
a) geometry of scintillator tiles
b) wrapping in aluminum foil
c) read out by four SIPM serially connected





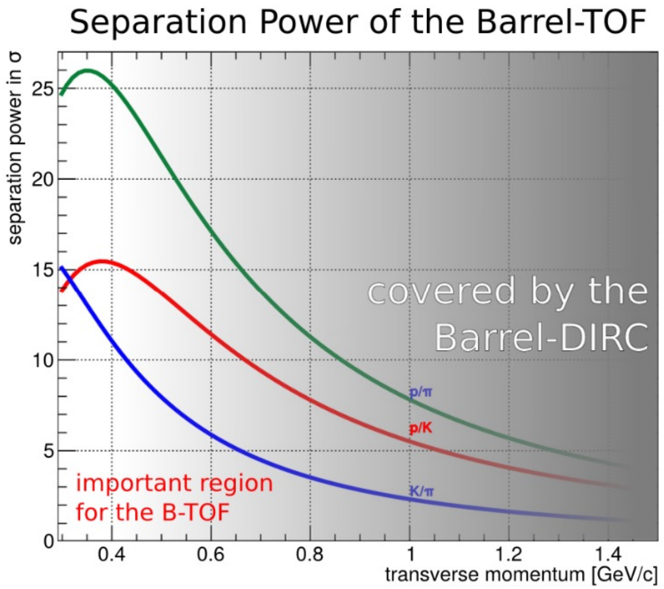
resolution improves from 110-180 ps to 45 ps

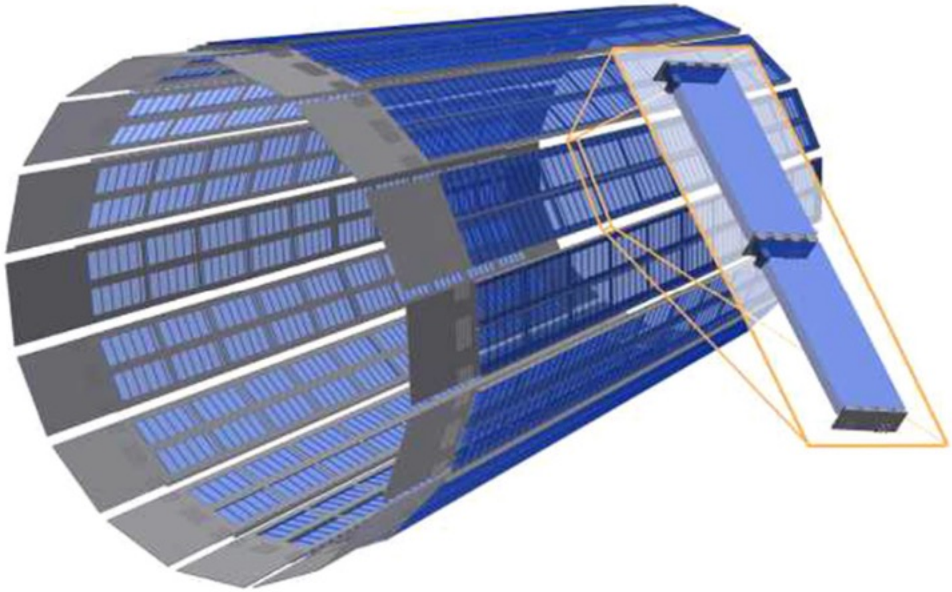
Design optimization for TOF SiPM based readout scales with $N_{ph.}$ → serial connection

@GSI-FAIR/Germany

TOF SiPM based readout: PANDA example

Istituto Nazionale di Fisica Nucleare





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HPK S13360 currently indicated as selected SIPM in PANDA TDR with 50-60 ps resolution
https://panda.gsi.de/system/files/user_uploads/ken.suzuki/RE-TDR-2016-003_0.pdf
https://doi.org/10.1016/j.nima.2018.11.094
PANDA identifies hybrid mode
→ parallel connection for V_{bias}
→ series for signal with decoupling capacitor

@ISS/ → Space application!

Note AMS-100 for its TOF using PANDA approach + HPK S14161 reaches below 40 ps (with ^{90}Sr)
Instruments **2022**, *6*(1), 14

Intermezzo: basics of TOF scint+SiPM readout

$$\sigma_t^{ph} \propto \sqrt{\frac{\tau_r\,\tau_d}{N_{det}}} \propto \sqrt{\frac{\tau_r\,\tau_d}{N_{ph}\cdot QE\cdot CE\cdot G}}$$

"scintillator quality"

PDE x GAIN (+ DCR) --> SiPM quality

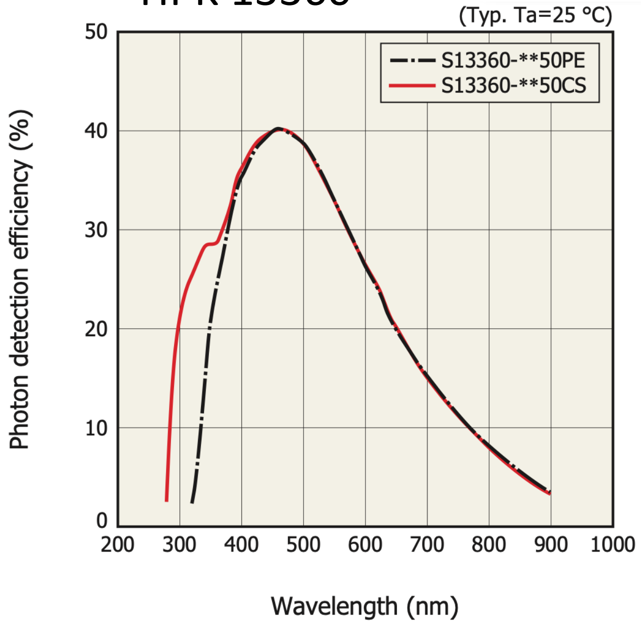
PDE

scintillator rise and decay time
number of detected photons

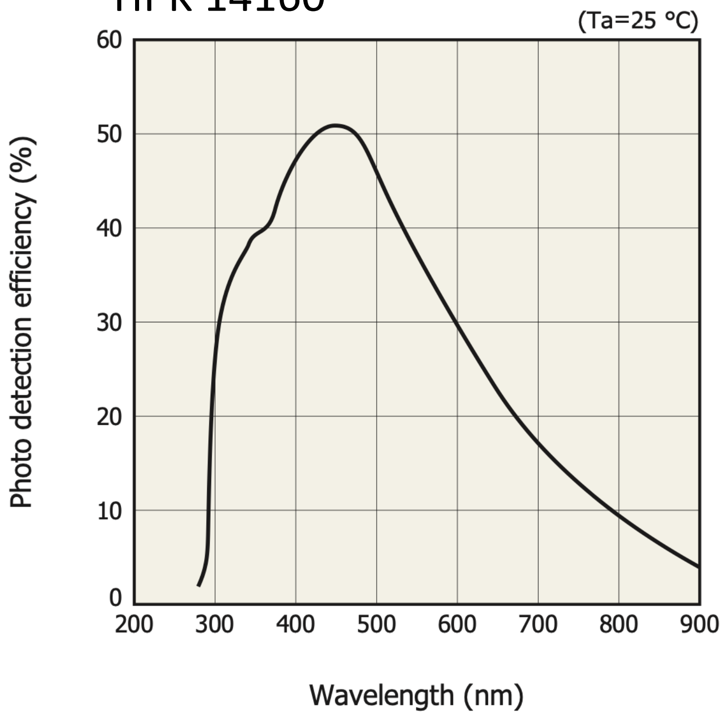
S14 w.r.t. S13 a higher PDE (50% at λ_{peak}=450 nm, V_{bias}=V_{BD}+2.7 V) lower crosstalk, a higher gain O(10^6) lower breakdown voltage (V_{BD}=38 V).

S14 w.r.t. S12 : afterpulse and DCR reduced by two orders of magnitude

HPK 13360



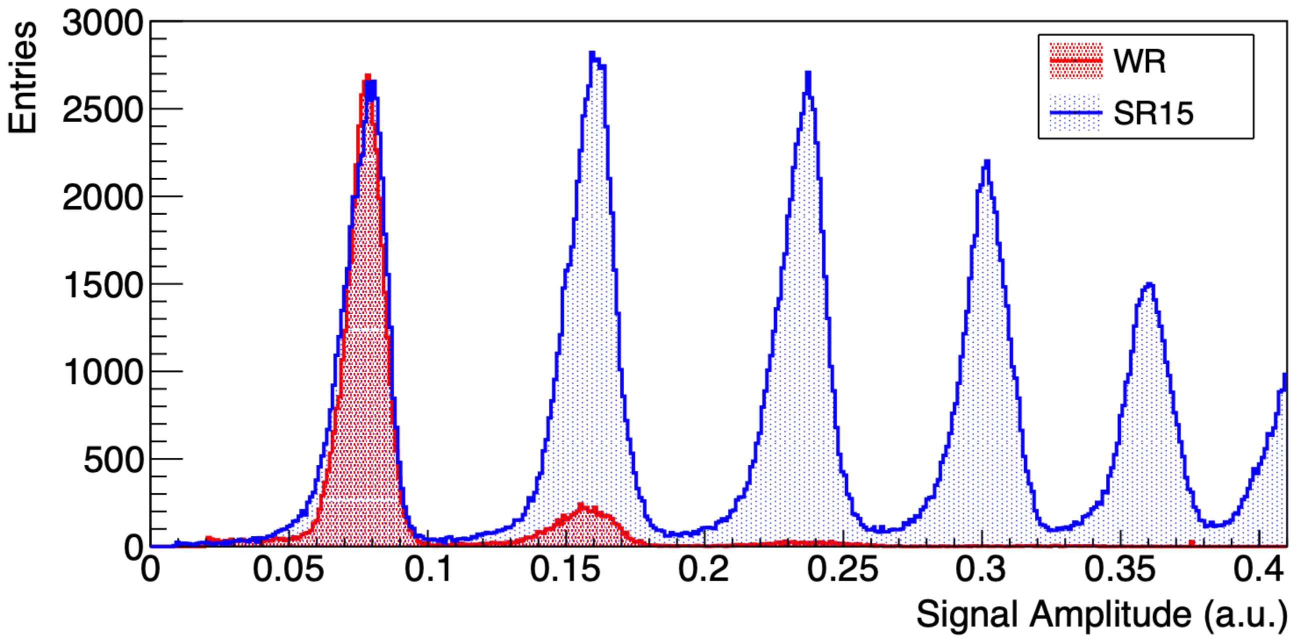
HPK 14160



https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s13360_series_kapd1052e.pdf

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160_s14161_series_kapd1064e.pdf

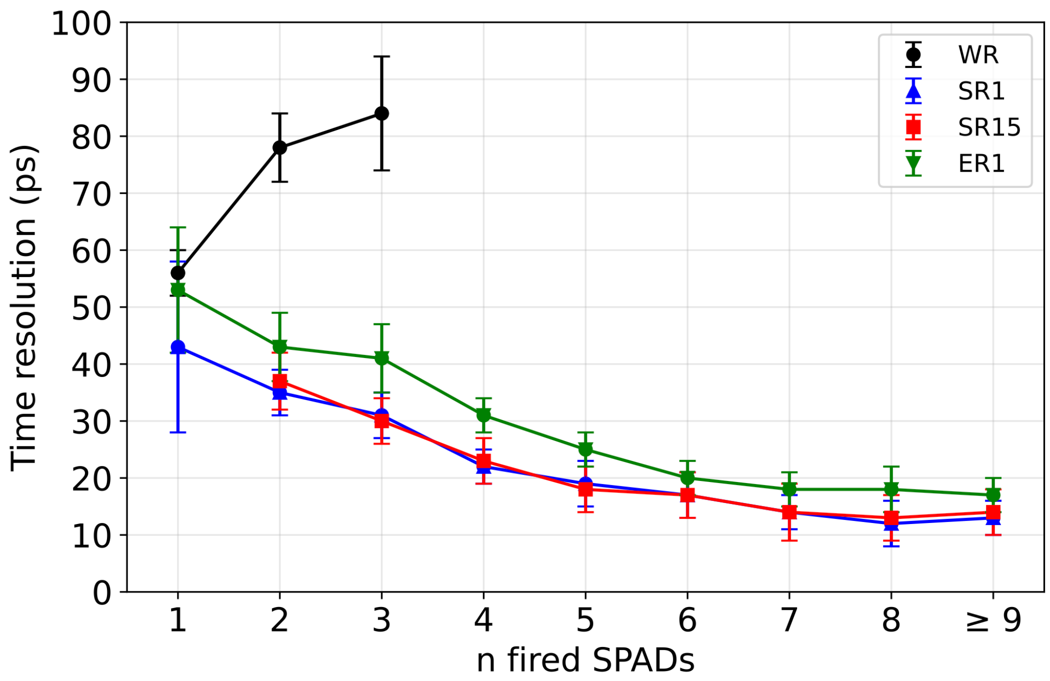
SiPM as charged particle detectors?



recent results exploited Cerenkov light produced in protective resin of the entrance window making SiPM sensitive to MIP

potential for "compact TOF" (no scintillator!)

potential to make RICH+TOF with SiPM as photosensor



F. Carnesecchi et al., https://arxiv.org/pdf/2210.13244.pdf
F. Carnesecchi et al 2022 JINST 17 P06007

Note:
F. Gramuglia et al, https://arxiv.org/abs/2111.09998v1
shows results with APD implemented in CMOS tech sensitive to MIP (primary ionization in the silicon)

https://doi.org/10.48550/arXiv.2305.17762

RICH+TOF?

@CERN/Switzerland

Note Cerenkov light + TOF is "old" idea:

- Y.Enari NIM A547 (2005) 490 https://doi.org/10.1016/j.nima.2005.03.159 “TOP”counter
- K.Inami NIM A560 (2006) 303 TOF counter with MCP-PMT
- ALICE T0 detector based on same idea (http://dx.doi.org/10.1109/NSSMIC.2004.1462267)

But:

SiPM (“MIP enabled”) could be a compact readout choice for a TOF+RICH

*Take home message

ALICE3 TOF+RICH, if realized, would be by far largest SiPM instrumented area (39 m^2) for a RICH and a TOF detector

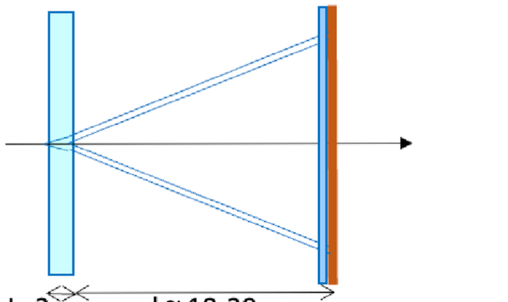
Currently discussed in the context of ALICE 3 Letter of Intent https://arxiv.org/abs/2211.02491

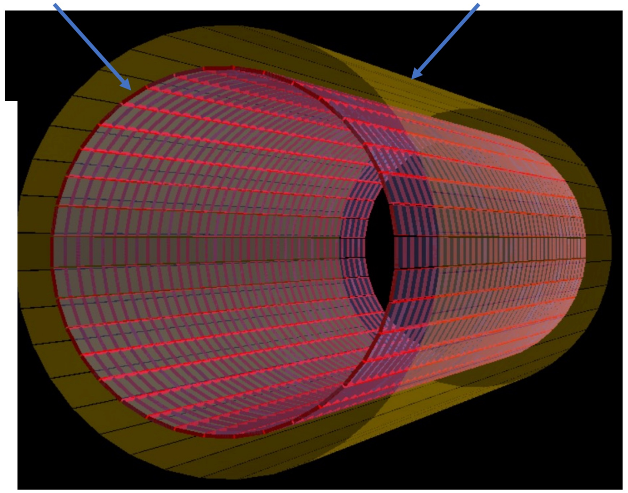
“An appealing possibility would be a sensor to detect both MIPs and single photons with high efficiency and good timing capability, such that it can be used both for Cherenkov detection and Time of Flight (TOF) applications.”

For TOF applications: 1 mm SiO_2 + 0.45 mm epoxy layer considered on top of Commercial HPK 13360

This design choice would allow one to recover expansion space after radiator (no need of a 2nd TOF layer)

2035 horizon can help to factorize photosensor developments





Some exploratory technologies developments about SiPM

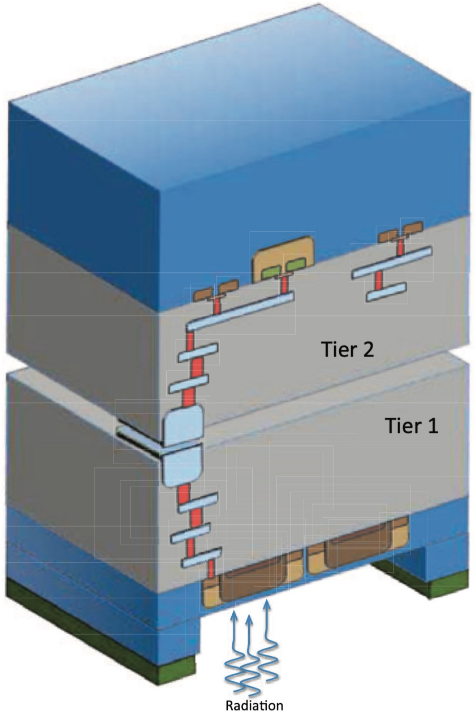
CMOS/3D integration?

https://doi-org.ezproxy.cern.ch/10.1109/NSSMIC.2014.7431246

E. Charbon et al, A Dual Backside-Illuminated 800-Cell Multi- Channel Digital SiPM with 100 TDCs in 130nm 3D IC Technology

The SiPM was fabricated in a two-tier 130nm CMOS process; the top tier houses 1600 single-photon avalanche diodes (SPADs), organized in a dual 4x200 linear array; the bottom tier houses 2x100 time-to-digital converters (TDCs). Every 8 SPADs there is one shared TDC whose digital output is routed to a 1.04Gps readout interface that enables a total count rate of 80Mcps

- Very interesting (and challenging) design... no revolution since 2014....
- Digital SiPM triggered wide interest 10 years ago but didn't reach the market
- Philips discontinued Digital SiPM → CMOS process results in a more "noisy" sensor
- Excellent review (from Sherbrooke group): toward "Photon-to-Digital Converter" (PDC) *Sensors* **2021**, *21*, 598. https://doi.org/10.3390/s21020598



Remember:

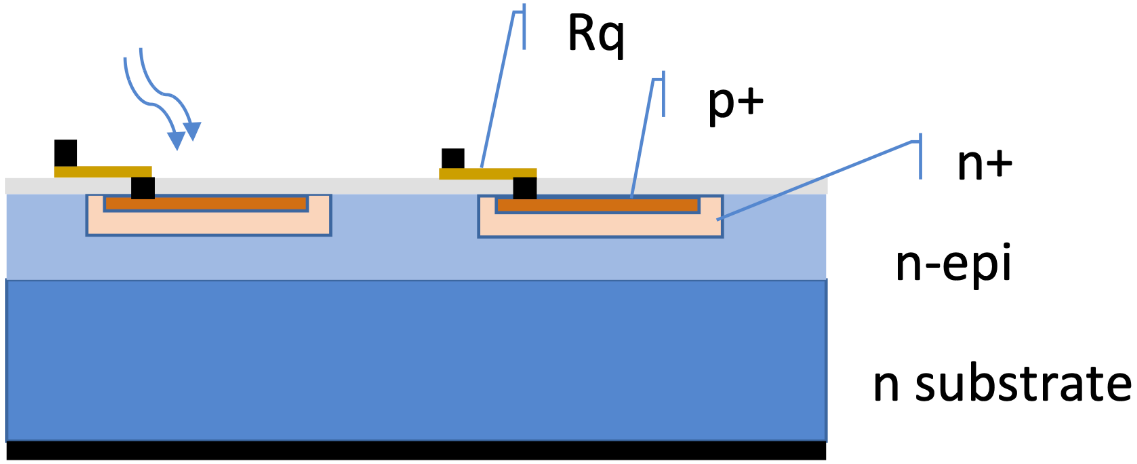
nowadays IC are based on Complementary Metal-Oxide Semiconductor (CMOS) technology.
CMOS transistors are based on MOSFET transistors and incorporates both PMOS and NMOS transistors, using complementary PMOS-NMOS pairs.

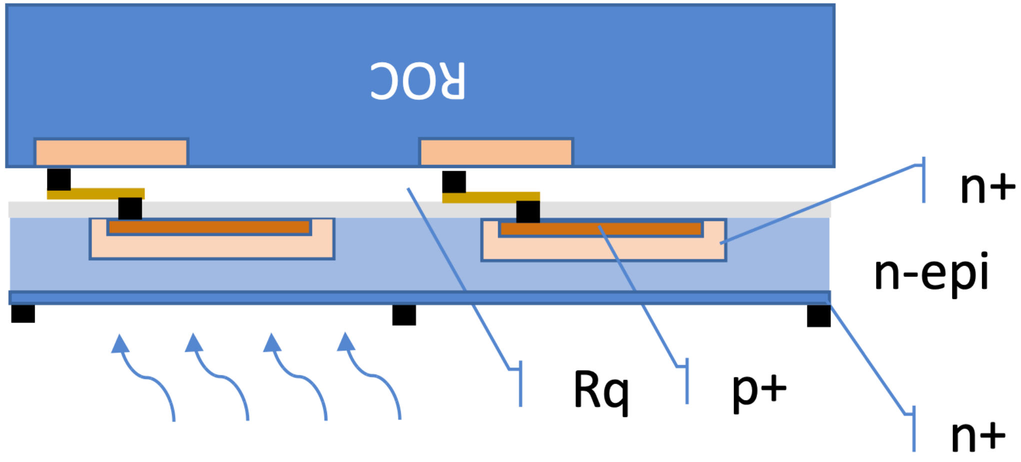
*Take home message

- CMOS technology could make access to commercial technologies but heating from digital circuitry is something to be studied. Unclear if "doable"
- 3D Integration (instead of a pure CMOS) process could be way forward

Backside illuminated (BSI) SiPM?

Credits: A. Montanari

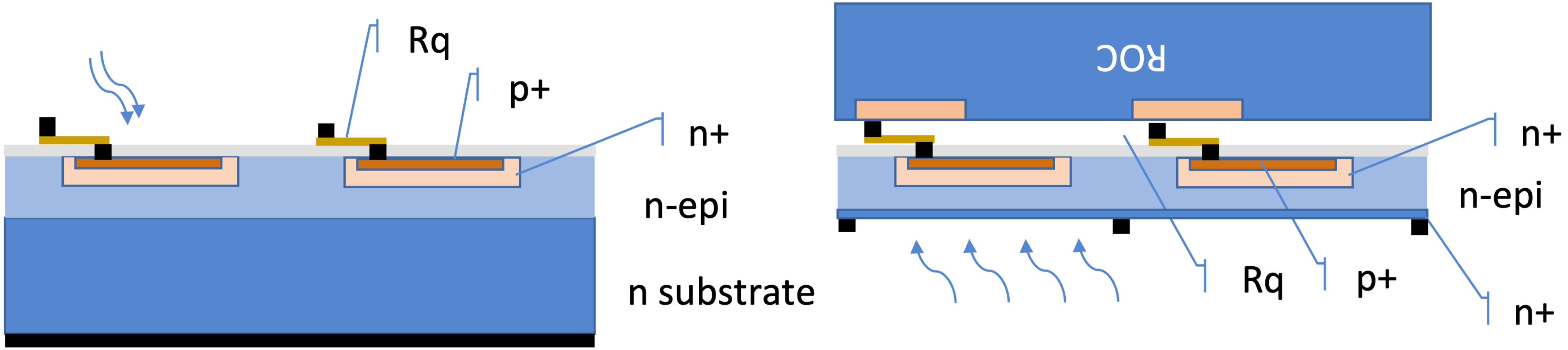




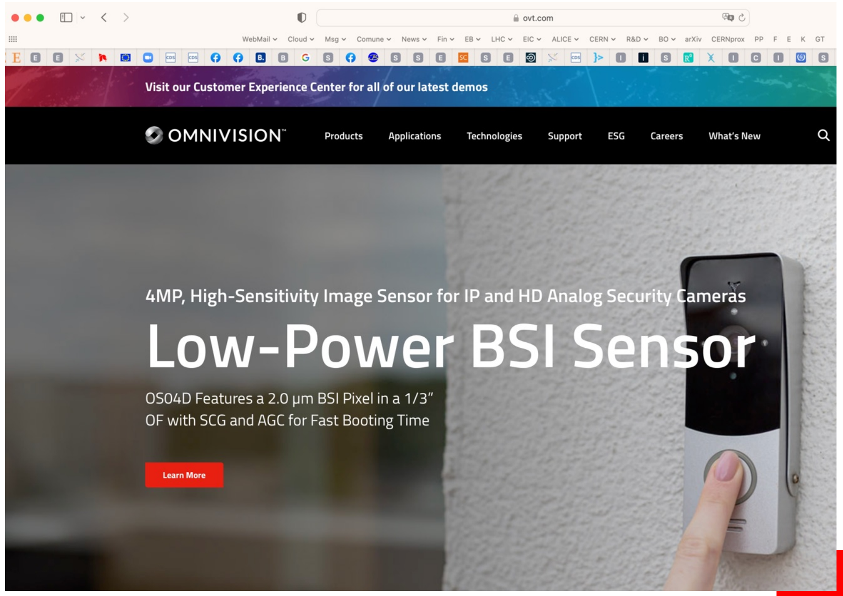
- BSI SiPM would have the obvious advantage of “easy” implementation / routing of readout + increase FF
- Actively researched also in the context of BelleII RICH upgrade (>2030) + AIDAInnova + DUNE + many groups...

Backside illuminated (BSI) SiPM?

Credits: A. Montanari



- BSI SiPM would have the obvious advantage of "easy" implementation / routing of readout + increase FF
- Actively researched also in the context of BelleII RICH upgrade (>2030)
- BSI is now industry standard for consumer and professional imaging sensors (ex. here Omnivision company)
  Sensors **2018**, *18*(2), 667; https://doi.org/10.3390/s18020667

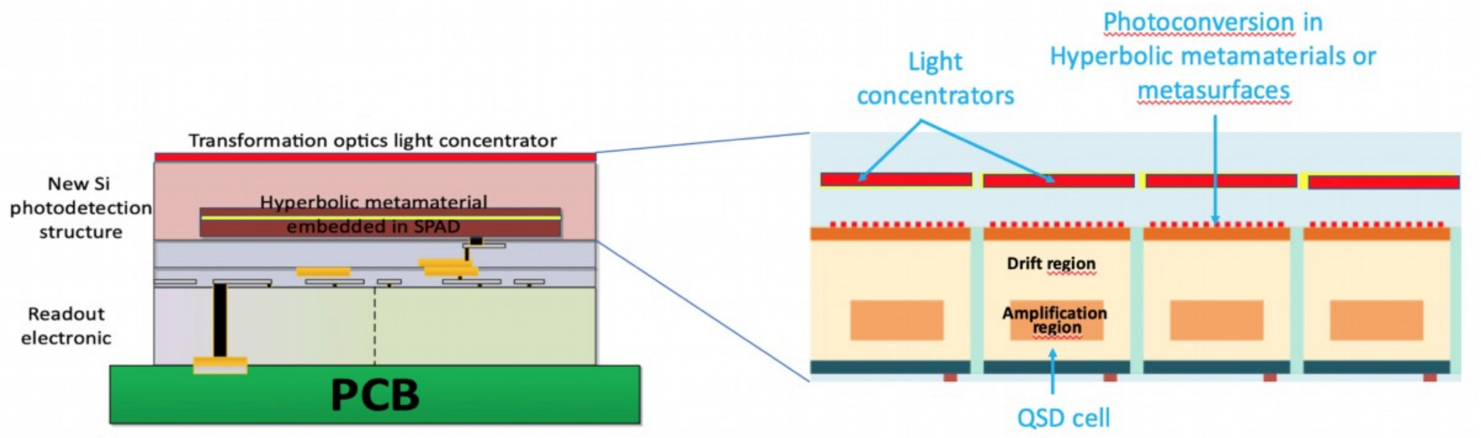


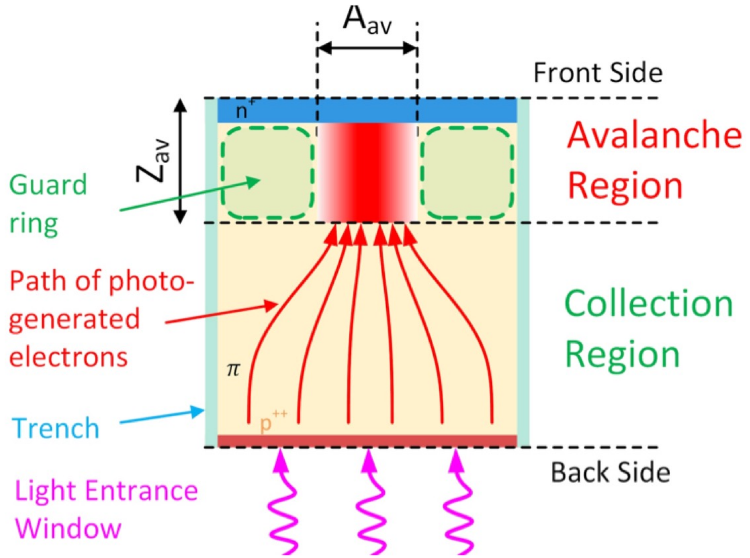
Backside Illuminated (BSI) SiPM as one of the "brick" of next generation SiPM?

S. Enoch et al., Design considerations for a new generation of SiPMs with unprecedented timing resolution
https://doi.org/10.48550/arXiv.2101.02952 |
JINST 16 (2021) 02, P02019

[CERN , INFN-TO, FBK, CNRS (Inst. Fresnel), UPV/Spain]

Proposed "Quantum Silicon Detector"





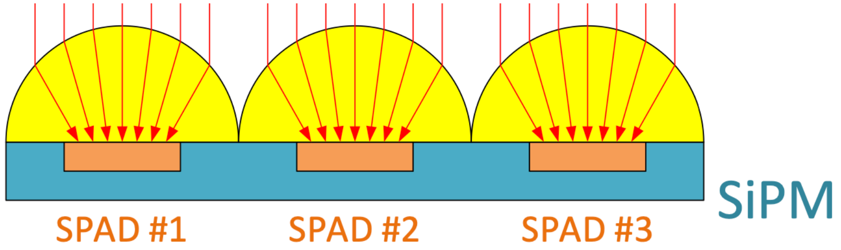
2021 paper that captures together several R&D trends:

- How to try to implement 3D SiPM getting CMOS tech. elements
- Enhanced optical entrance (light concentrator + metalenses)
- Smaller cell size → less radiation damage
- smaller τ_r → faster recovery time

Microlenses / metamaterials

Microlenses to enhance radiation hardness

- Photons can be focused on a much smaller light-sensitive area within each microcell.
- The silicon *area sensitive to radiation damage is reduced*.



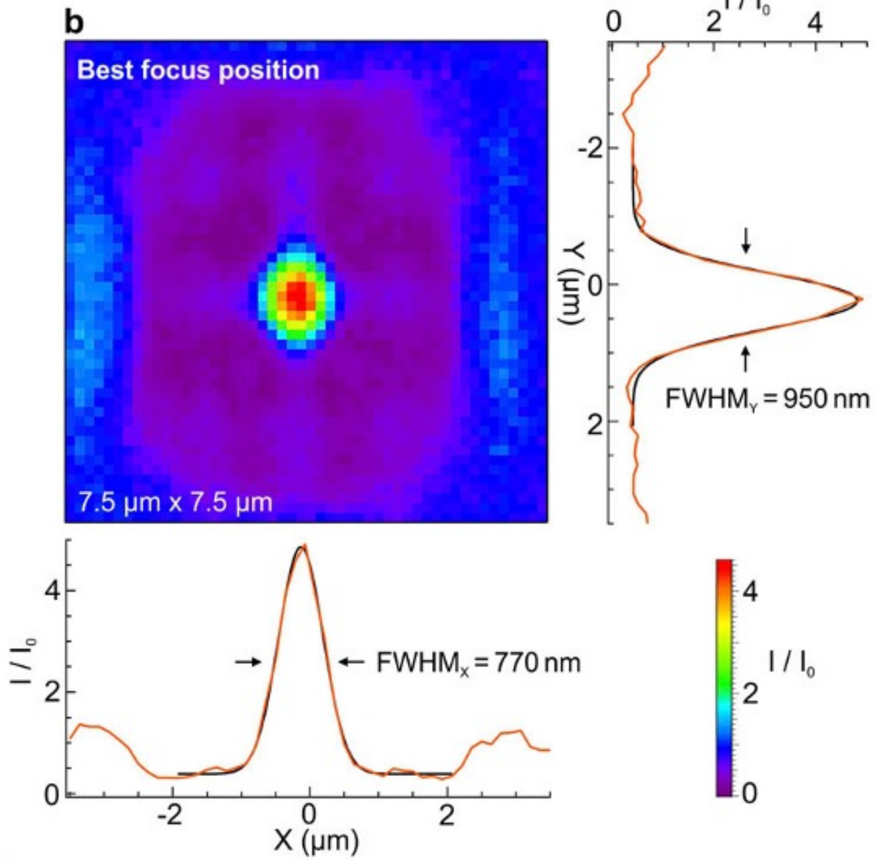
Courtesy from A. Gola @RICH2022

*Take home message

We can't avoid neutrons to hit silicon in the "sensitive damage regions", but we can curb their area/volume

Microlenses can be used to enhance the Fill Factor (FF) and thus the PDE of the SiPM microcells

Metamaterials for microlensing realized in CMOS compatibile process using Nb_2O_5
E. Mikheeva et al, APL Photonics 5 (2020) 116105



Anti-Reflective coating (ARC)

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Article | Open Access | Published: 16 August 2022

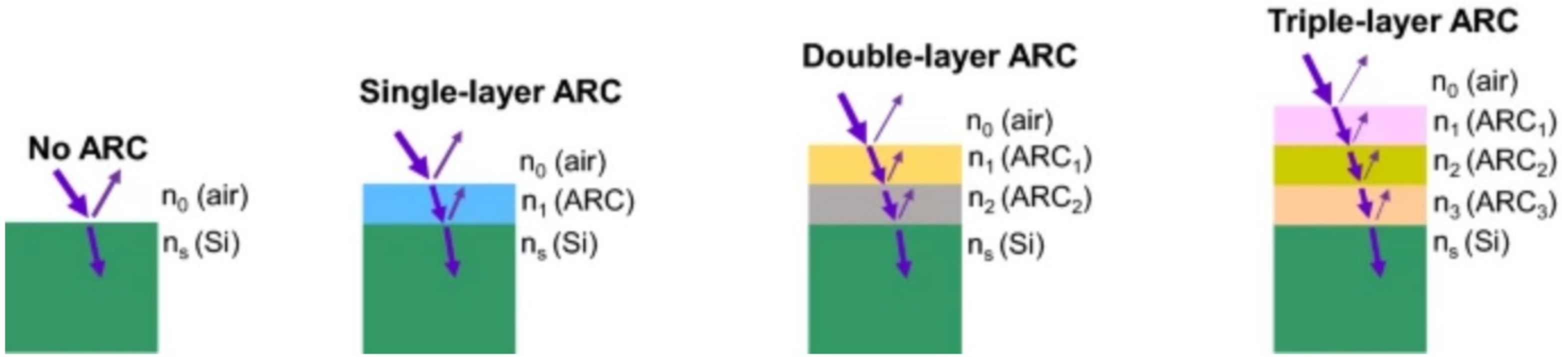
Advanced antireflection for back-illuminated silicon photomultipliers to detect faint light

Yuguo Tao, Arith Rajapakse & Anna Erickson

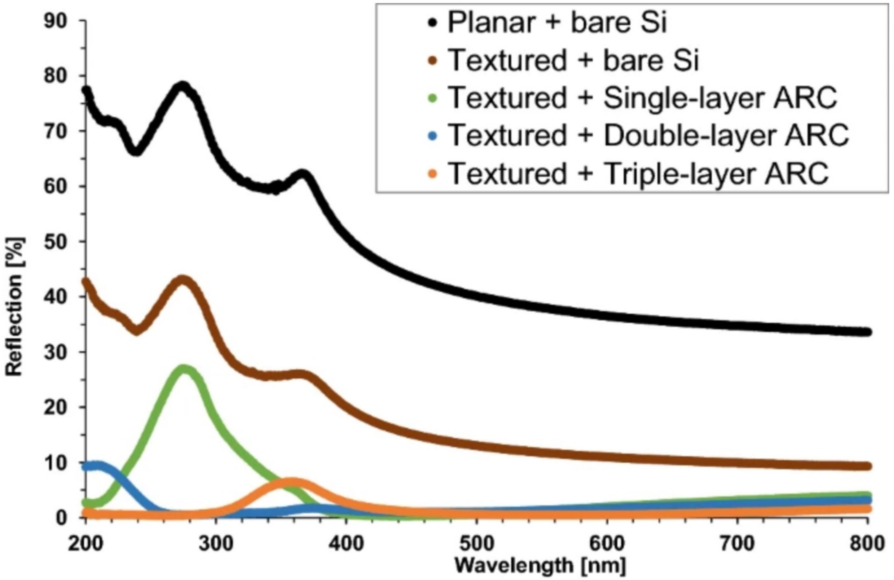
Scientific Reports **12**, Article number: 13906 (2022) | Cite this article

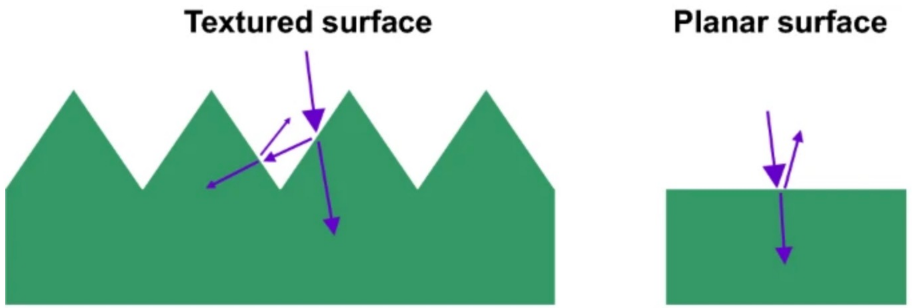
https://doi.org/10.1038/s41598-022-18280-y

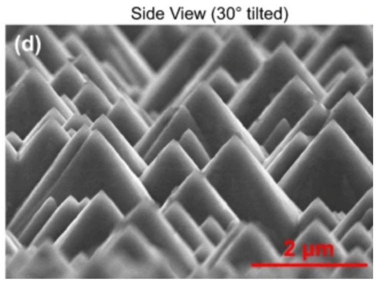
Standard SIPM: ARC materials are thermally grown silicon dioxide (SiO_2) or SiNx /typically one layer



multi-layer ARC on textured surface with upright nano-micro pyramids to reduce the reflection + DARC/TARC







*Take home message

Combining ARC developments with BSI could be far reaching in FF and PDE for SiPM

(Some) conclusions

*Take home message

SiPM is a very dynamic field of research

- SiPM request for NP/HEP will increase: orders by several O(1-10 m^2) !
- SiPM might extend its application to Cerenkov/PID (single photon application) within next 7-10 years
- For large scale applications cooling (as well as in-situ annealing techniques) will be key part of detectors with SiPM-based readout, especially for Cerenkov applications
- There are several technologies developments to be closely watched/followed by our community. Combined all together they might enable SiPM "radiation *tolerant* because, despite the damage, they still fit for purpose" with a unprecedented timing resolution and PDE
- And… SiPM are ubiquitous… not only in HEP/NP…

Why Use SiPM Sensors for Automotive LiDAR Applications?

by Deborah Herbert - 03-01-2021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Home › Soluzioni › Attivi › Il primo sensore SiPM qualificato per uso automotive destinato ad applicazioni LiDAR

Il primo sensore SiPM qualificato per uso automotive destinato ad applicazioni LiDAR

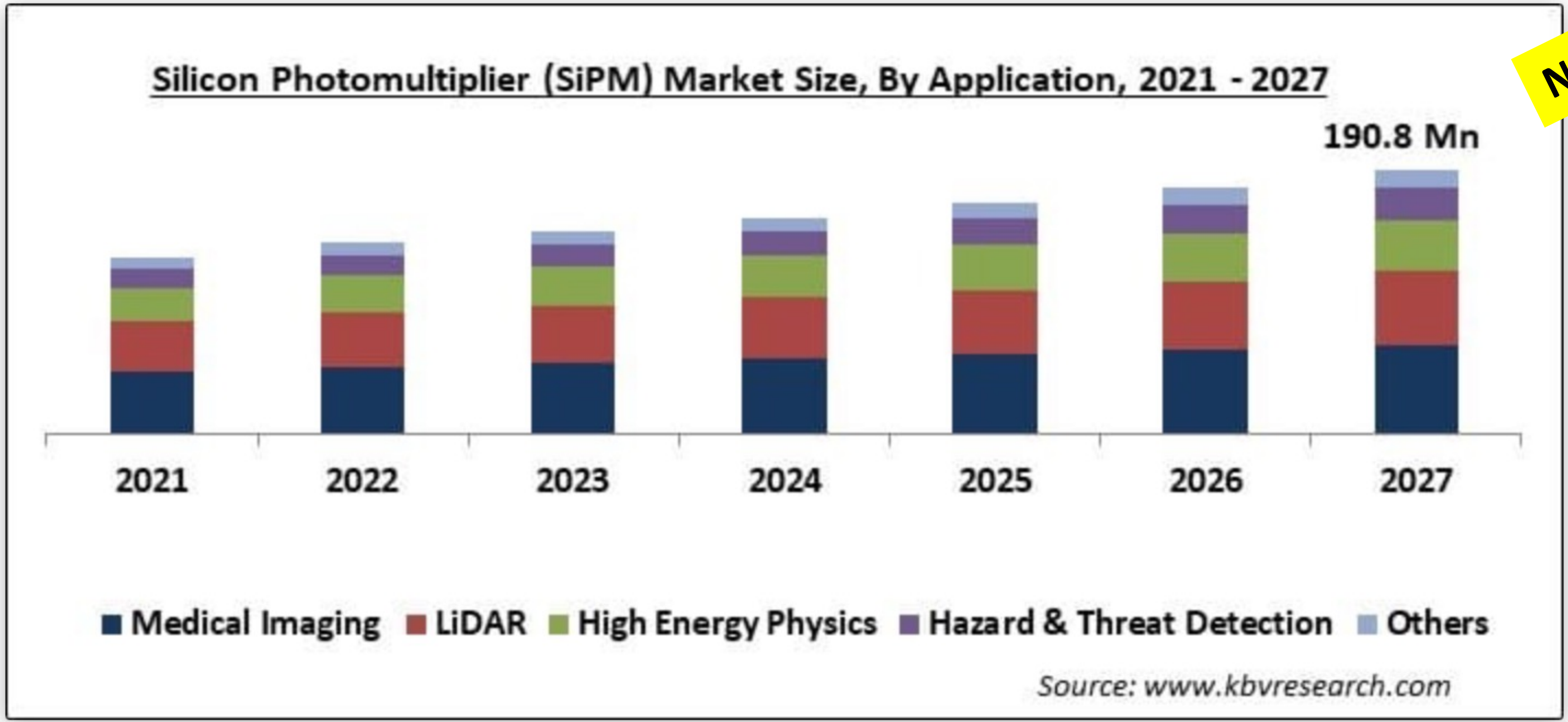
Di Massimiliano Luce - 11 Marzo 2021

https://www.onsemi.com/company/news-media/blog/automotive/sipm-sensors-automotive-lidar-applications

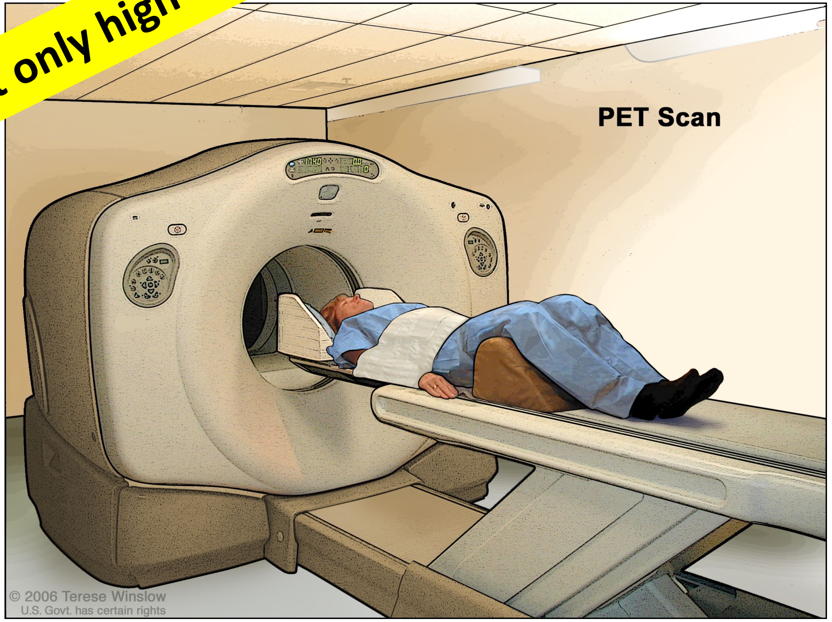
SiPM applications in positron emission tomography: toward ultimate PET time-of-flight resolution

https://doi.org/10.1140/epjp/s13360-021-01183-8

P. Lecoq[1,2,a], S. Gundacker[1,3,4]



Not only high energy physics!



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  https://cds.cern.ch/record/2738368/files/Gundacker_2020_Phys._Med._Biol._65_17TR01.pdf